

DEVELOPMENT AND EVALUATION OF THE OCD/API MODEL

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Development and Evaluation of the OCD/API (Offshore and Coastal Dispersion/American Petroleum Institute) Model

**Prepared for the American Petroleum Institute
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Executive Summary

The Offshore and Coastal Dispersion (OCD) model (version 3.0) was developed by the MMS for applications in which the onshore impact of plumes released from offshore sources (e.g., oil platforms, tankers) must be calculated. However, the OCD/3.0 model does not contain adequately-tested algorithms for complex terrain impaction, fumigation, or platform downwash. The purpose of this project was to modify the model to better account for these phenomena and evaluate the model with the Carpinteria tracer data. Our major conclusion is that the new OCD/API model produces concentration predictions in very good agreement with the Carpinteria tracer data, which were obtained at a steep coastline. Furthermore, the new model predictions are not significantly different from the OCD/3.0 model predictions at the flat terrain experiment sites used in the original evaluation of the OCD/3.0 model. Specific findings are listed below:

- 1) The following specific changes were made in order to create the new OCD/API model:
 - Petersen's platform downwash algorithm was added to the code.
 - The definition of effective mixing depth at the shoreline was changed to better account for the finite depth of the plume material.
 - The shape factor for lateral dispersion was altered such that σ_y was reduced by about 30% at a downwind distance of about 10 km. (The Draxler formula was substituted for the Briggs formula). The default lateral turbulence intensity was modified so that it is inversely proportional to the wind speed for all stabilities.
 - The Thermal Internal Boundary Layer (TIBL) formula was not changed but the new assumption was made that the TIBL is terrain following.
 - The Deardorff-Willis fumigation option was removed because it is found to have been derived for TIBL

slopes less than those typically observed, and the Turner option substituted (complete vertical mixing through the TIBL occurs as soon as the plume centerline intercepts the TIBL).

- The RTDM plume reflection formulas for complex terrain were dropped and the much simpler EPA TUPOS formulas added. Both formulas yield the same result, but the EPA method is more efficient.
- The critical streamline height approach was added to the complex terrain dispersion algorithm. If the plume is below this height, it impacts the terrain. If it is above this height, it flows up over the terrain.

2) API model evaluation procedures were applied to the observations and model predictions at the Carpinteria experimental site. The Carpinteria site is unique in that terrain is higher, wind speeds lighter, and the source closer to shore than in previous coastal dispersion experiments. The OCD/API, OCD/3.0, and OCD/CPM (an OCD version used in California) models were evaluated with both observed and predicted lateral turbulence intensity (i_y) options. The older CRSTER/OCS model was also evaluated using the 37 hourly periods.

- Overall Maximum C/Q (Concentration/Source Strength)

The OCD/API model shows a slight improvement over the OCD/3.0 model in its ability to predict overall maximum C/Q. The ratio of predicted to observed concentrations at the Carpinteria site for OCD/API with observed i_y is 0.95. The version with observed i_y performs better than the version with predicted i_y .

- Maximum C/Q for Each Hour

The normalized mean bias, FB, and the normalized mean square error, NMSE, were calculated (with 95% confidence limits) for each model. The OCD/API model performs significantly better than the

OCD/3.0, the OCD/CPM and the MMS models at the Carpinteria site. The FB is 0.14 and the NMSE is 0.76 for OCD/API with observed i_y .

It is seen that the performance of the OCD/3.0 and OCD/CPM models at Carpinteria is similar.

3) Other Experimental Sites

In order to make sure that the performance of the new OCD/API model is adequate at the flat terrain experimental sites used in the original evaluation of the OCD/3.0 model, the statistics were run for the Pismo Beach, Ventura, and Cameron sites. No significant difference is evident in the performance of the OCD/3.0 and OCD/API models. In general, the models perform slightly better if observed lateral turbulence, i_y , is used.

4) Gaviota Experiment

The Gaviota tracer data were reviewed and added to the set of experiments used for model evaluation. Terrain is very steep at that site, and the tracer plume generally did not directly impact the slope. All models overpredict at Gaviota because the assumption is made that the plume centerline is pointed towards one of the receptors, whereas the actual plume veers away from the terrain. Consequently the Gaviota results are not included in the calculation of medians over all experiments.

Recommendation On the basis of these findings, it is recommended that the OCD/API model be used in place of the OCD/3.0 model for applications where the air quality impact of offshore sources must be assessed.

1. Introduction

The Minerals Management Service (MMS) now requires modeling of emissions sources in federal coastal waters prior to permitting new platforms. Use of the Offshore and Coastal Dispersion (OCD) model is mandated for these applications. However, the OCD model was developed and tested primarily for coastal regions where the terrain is relatively flat (Hanna et al., 1985). Many recent applications, on the other hand, have involved portions of the California coast where the terrain is steep near the shoreline. The purpose of the current study is to modify the model (OCD/3.0) used by the MMS so that it better handles steep coastlines, and compare the performance of the modified model (OCD/API) with the performance of the original OCD/3.0 model using tracer data from an experiment in a region with steep terrain. The following technical tasks were carried out:

- Modification of OCD complex terrain algorithm.
- Modification of OCD shoreline fumigation algorithm.
- Modification of plume meander algorithm.
- Installation of revised platform wake algorithm.

In order to provide data for testing and modifying the OCD model in complex terrain, the API sponsored a tracer study of dispersion in the Carpinteria, CA, area (Johnson and Spangler, 1985). Two neutrally-buoyant tracers were released from elevated point sources about 300-1000 m offshore, about 40 air samplers were situated on the steep terrain onshore, supporting meteorological data were taken both off-shore and on-shore, and a helicopter obtained supporting tracer and meteorological data. Two separate sets of experiments were done: the first emphasized terrain effects and concentrated on the region with a steep 50 m cliff at the shoreline; the second emphasized fumigation and took place in a region with gentler terrain at a location west of the first site. Steep mountains rising to an elevation of 1500 m are located a few kilometers inland in both experiment regions. A map of the site and the monitor locations for the terrain effects experiments is given in Figure 1-1. Further discussion of the site and the experimental results will be given in Sections 2 and 4.

In the course of the study it was discovered that many algorithms in the OCD code could be improved. Some specific analyses performed using data from Carpinteria and from other sites are discussed in Section 2, including a test of whether the wind direction distribution at Carpinteria is Gaussian, a comparison of

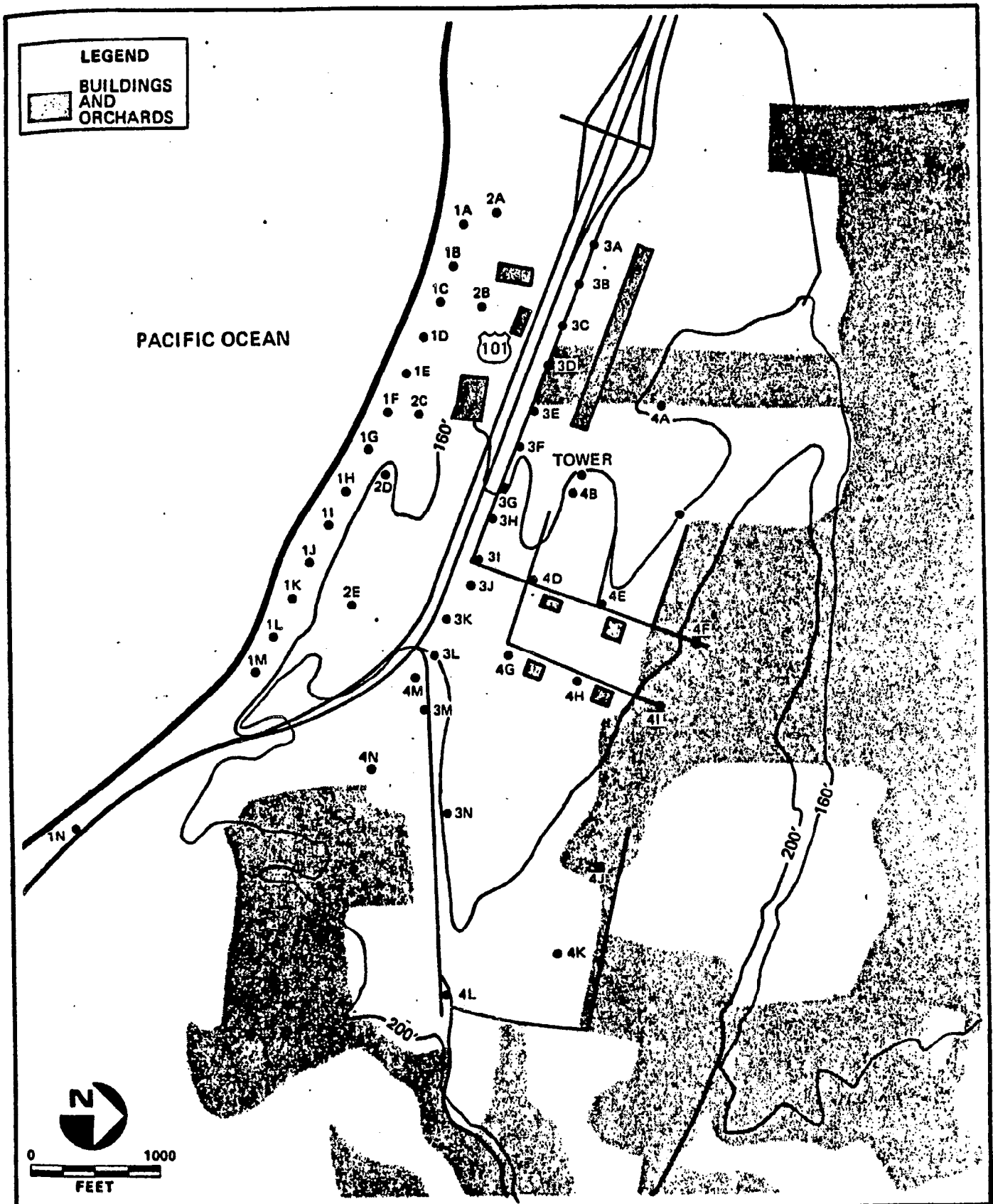


Figure 1-1. Tracer Sampling Sites Used in the Terrain Effects Portion of the Carpinteria, CA Experiment

observed and predicted lateral dispersion σ_y at Carpinteria, and a study of the height of the Thermal Internal Boundary Layer (TIBL) at several sites. Section 3 contains a comprehensive summary of all changes that were made in the process of developing the OCD/API code. Revised equations are given where appropriate.

Experimental data were available to test the lateral terms in the revised model equations. However, there were no vertical profiles of tracer gas measured, thus making it impossible to test specific components of the vertical terms, such as vertical dispersion σ_z , plume height, fumigation rate, and TIBL behavior. But very few field experiments anywhere provide even portions of these vertical terms, thus requiring implicit validation of the vertical terms through comparisons with ground level concentration distributions.

The model evaluation procedures and results are given in Section 4 for the Carpinteria tracer study. For completeness the new model is evaluated in Appendix A for the six experiments used by Hanna et al. (1984) in their evaluation of the OCD/3.0 model, and for the Gaviota tracer study, which is characterized by very steep terrain. Further appendices contain a complete set of meteorological data from the experiments, a listing of the OCD/API code, a description of required input procedures, and a discussion of a sample run. Interested persons can obtain copies of the information in the appendices on an IBM-PC compatible floppy disk from the authors.

2. Analyses of Model Components

As a background for possible modifications to the OCD model, some specific analyses were performed using data from Carpinteria and from similar tracer experiments at Ventura, Pismo Beach, and Cameron. Some of the studies which yielded more tangible results are listed below.

2.1 Gaussian Fit to Wind Direction Fluctuations

The OCD/3.0 model assumes that the lateral concentration distribution has a Gaussian shape. Most models use this assumption, which is based on the knowledge that turbulent fluctuations in the atmosphere are usually Gaussian. An alternative approach is to assume that the lateral concentration distribution has the same probability density function (pdf) as the wind direction distribution. However, this approach requires more detailed data input and increases the complexity of the model. In order to decide whether the more complex pdf approach was needed, a study of the Carpinteria wind direction data was conducted. To test whether or not a given wind direction pdf is Gaussian, the BIOSSTAT statistical analysis program was applied to 17 hours of one second wind direction data from Carpinteria.

The skewness and kurtosis of the distributions were calculated for each hour. It was found that individual hours could be positively or negatively skewed, but there was no preference in any one direction. The kurtosis analysis, on the other hand, suggested that most of the observed pdf's were flatter (i.e., had wider tails) than a Gaussian pdf would give. The Kolmogorov-Smirnov test of good fit showed that the hypothesis that the pdf was Gaussian for all hours could be rejected (with 99% confidence). Examples of pdf's (in the form of histograms) are given in Figures 2-1 and 2-2. The pdf in Figure 2-1 is close to Gaussian, which tends to occur with moderate to high wind speeds. The pdf in Figure 2-2 is clearly non-Gaussian, since it is broad (range of 135°) and has two distinct peaks.

It would appear from these results that the wind direction pdf is sufficiently non-Gaussian to warrant use of the actual pdf in a dispersion model. However when this was tried using the Carpinteria data for the cases in Figures 2-1 and 2-2, the concentration predictions by the model did not improve. Perhaps the randomness, uncertainty, and unrepresentativeness of the wind data are so great that the pdf of the wind direction data does not match the pdf of the ground level concentration data. This conclusion was also reached by Hanna et al. (1986) in their analysis of the much more extensive EPRI Kincaid tracer data set.

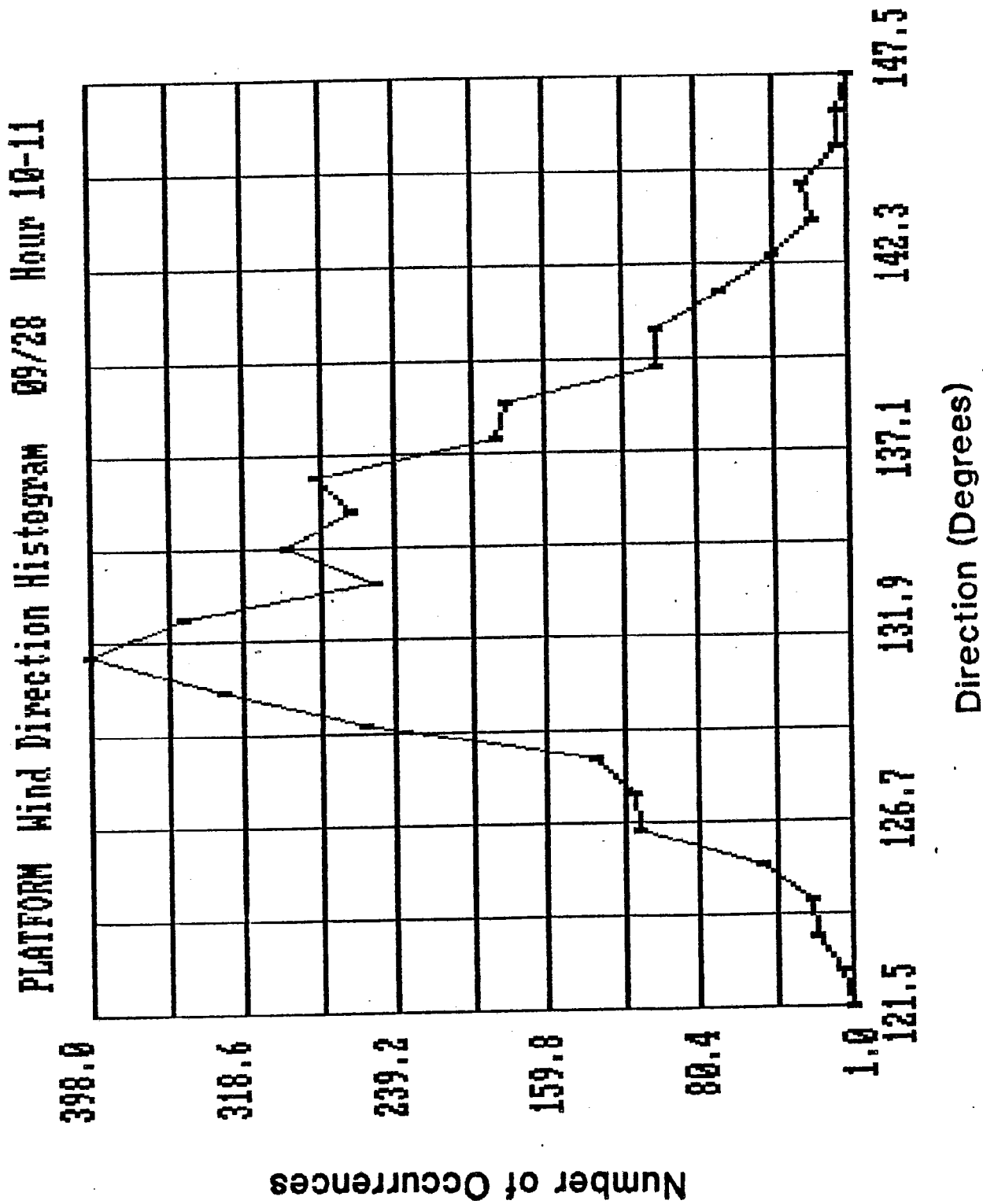


Figure 2-1. Platform Wind Direction Histogram from Carpinteria Experiment Number 7, Hour 11. The Basic Wind Direction Data are One Second Averages.

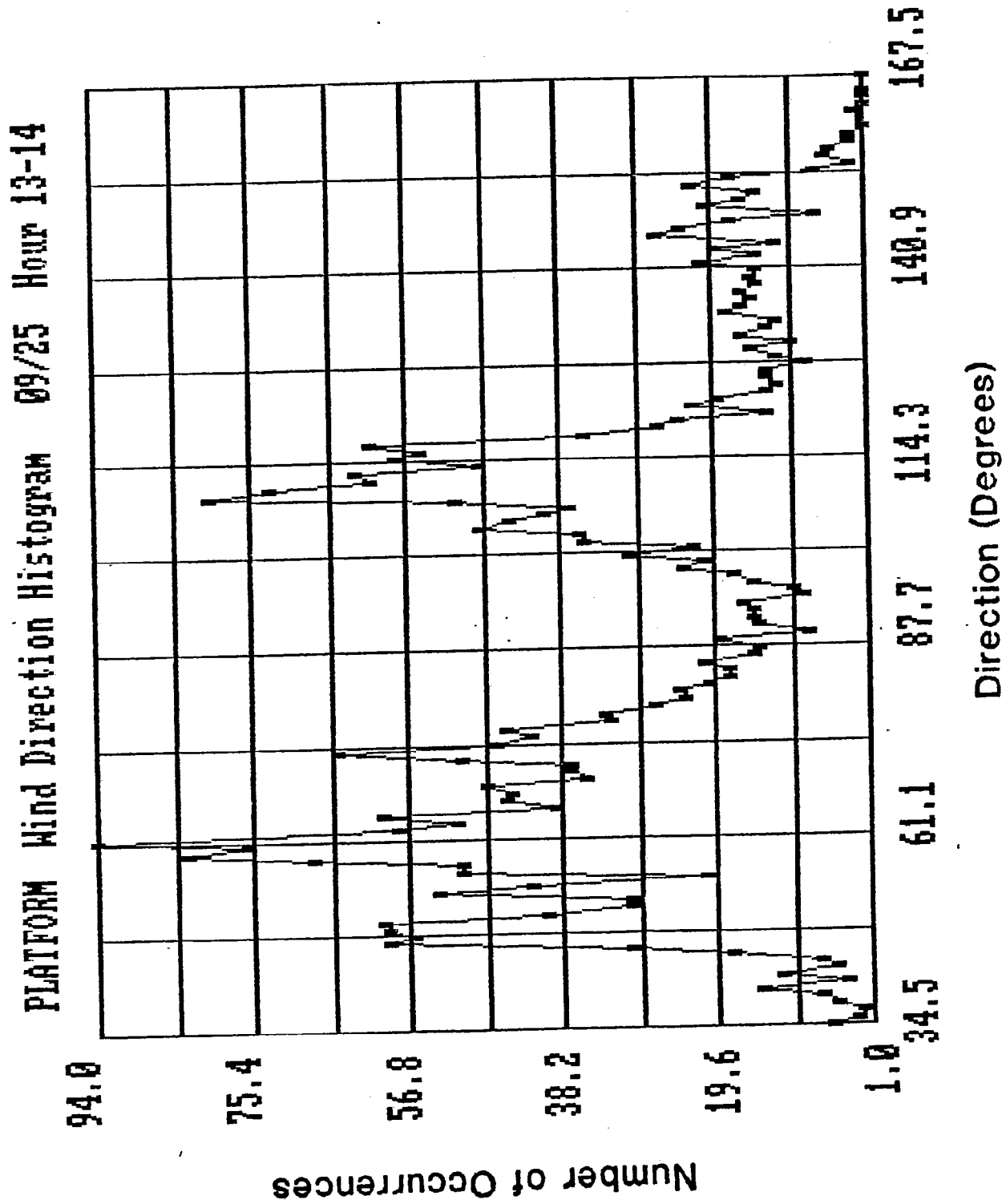


Figure 2-2. Platform Wind Direction Histogram from Carpinteria Experiment Number 5, Hour 14. The Basic Wind Direction Data are One Second Average.

At that site, the mean wind direction differed by the observed plume direction by about $\pm 20^\circ$. Because of the greatly increased data collection requirements and the added complexity to the model, it was concluded that the use of the pdf approach was not justified at this time.

2.2 Analysis of σ_y at Carpinteria

The Carpinteria field study provided cross-wind distributions of tracer concentrations that could be used to directly calculate σ_y . A map of the monitor locations was shown in Figure 1-1. In this subsection, the observed and OCD/3.0 predicted σ_y values are compared.

Figure 1-1 shows that there is a well-defined shoreline arc of monitors and a more widely-spaced inland arc. Despite the wide coverage of the monitors, the plume was often so wide that the monitoring network did not capture all of the plume. These cases are marked by asterisks in Table 2-1.

Monitoring data were used to calculate σ_y by a method in which the distance between the 16th and 84th percentiles of the cross-wind cumulative distribution of C is assumed to equal $2 \sigma_y$. This method is more robust (i.e., less influenced by outliers) than the often-used moment method. Table 2-1 contains observed and predicted σ_y 's for the SF₆ and Freon data. Almost half of the observed σ_y 's have asterisks, suggesting that the plumes were at least partly off the edge of the network and the listed σ_y is probably an underestimate. A further indication of this problem is that the observed σ_y on the inland arc was less than the observed σ_y on the shoreline arc in about half of the runs. The arcs are about the same length, but the inland arc subtends less of an angle with respect to the source (60° versus 90°). Our analysis therefore emphasizes the data from the shoreline arc.

Figure 1-1 also shows that a single monitor, 1N, is isolated on the southern edge of the shoreline arc. That station was sited because it was suspected that the coastal terrain would sometimes turn plumes towards the south, parallel to the coast. However, monitor 1N often indicates significant concentrations and therefore strongly influences the σ_y calculation by either method. For example, for run 3-12, the observed σ_y is 250 m and 140 m with monitor 1N left in and out of the calculation, respectively.

The predictions of σ_y in Table 2-1 are made by three methods:

σ_{yp} (obs i_y) - OCD/3.0 model formulas are used with observed lateral turbulence intensity $i_y = \sigma_v/u$.

Table 2-1

Observed and Predicted σ_y for Carpinteria Study.

An Asterisk Following the σ_{yo} Estimate Indicates that the Plume was Off One or More Edges of the Network. Under σ_{yp} (pred i_y), Method 1 uses $0.5/u$ for only Stable Conditions, while Method 2 uses this Formula for All Conditions.

Shoreline Arc					
Run No. and Hour SF ₆	x (km)	σ_{yp} (obs i_y) (m)	σ_{yp} (pred i_y)		σ_{yo} (m)
			1	2	
1-9	1.1	520	70	440	380*
1-10	.8	390	50	320	220*
1-11	.7	290	42	114	250*
1-12	.9	580	57	150	150
3-9	1.2	680	57	1140	370*
3-10	1.5	450	78	550	440*
3-11	1.6	210	108	324	490
3-12	1.5	430	97	250	360
5-10	.7	620	370	370	660*
5-11	.8	200	350	350	680*
5-12	.8	370	350	350	110*
5-13	.7	210	320	320	231*
6-12	1.3	290	130	130	250
6-13			$C_p = 0$		
7-10	1.2	180	70	100	190
7-11	.8	160	54	130	420
7-13	1.2	220	84	390	320
7-14	1.1	220	71	250	570*
8-11	1.3	420	75	190	120
8-12	1.3	110	72	200	90
9-10	1.3	420			450*
11-930	1.0	210	465	465	450*
11-11	1.1	620	250	250	330*
12-10	1.1	250	Low C's		370
12-1030			Low C's		
12-11	.8	180	220	220	130*
13-10	1.0	530	44	420	Low C's
13-1030	1.1	370			Low C's
13-11	1.0	n.a.	58	480	250

Table 2-1 (Concluded)

Observed and Predicted σ_y for Carpinteria Study.

An Asterisk Following the σ_{yo} Estimate Indicates that the Plume was Off One or More Edges of the Network. Under σ_{yp} (pred i_y), Method 1 uses $0.5/u$ for only Stable Conditions, while Method 2 uses this Formula for All Conditions.

Run No. and Hour Freon	Shoreline Arc				
	x (km)	σ_{yp} (obs i_y) (m)	σ_{yp} 1 (pred i_y)	σ_{yp} 2 (pred i_y)	σ_{yo} (m)
3-11	1.2	160	84	250	150
3-12	1.3	380	85	220	400*
5-13	.8	260	380	380	140*
6-12	1.1	290	114	114	200*
6-13	1.1	280	114	114	470*
7-10	1.2	170	68	100	220*
7-11	.9	150	53	130	440
7-13	1.2	220	81	370	180
7-14	1.1	220	70	250	180*
8-12	1.2	100	67	180	all zeros

σ_{yp} (pred i_y) Method 1 - OCD/3.0 model formulas are used with predicted lateral turbulence intensity i_y , where $i_y = (0.5 \text{ m/s})/u(\text{m/s})$ only for stable conditions (this is the current OCD/3.0 procedure).

σ_{yp} (pred i_y) Method 2 - Same as Method 1, except $i_y = (0.5 \text{ m/s})/u(\text{m/s})$ is used for all stabilities (this is a revision to the current OCD procedure).

Method 2 was tested when it became apparent that the observed i_y values were much better simulated during unstable conditions by $i_y = (0.5 \text{ m/s})/u(\text{m/s})$ rather than by the boundary layer formulas in the OCD model. The wisdom of this change is seen in Figures 2-3, 2-4, and 2-5, where σ_y is significantly underpredicted during unstable conditions by the i_y formula in OCD/3.0 (see the points indicated by crosses in Figure 2-4). The predictions are in fair agreement with the observations when observed i_y is used or when predicted i_y (method 2) is used (see Figures 2-3 and 2-5). In Figure 2-3, the predictions are within a factor of two of the observations in 75% of the cases. This percentage is 68% in Figure 2-5. The median observed and predicted values are 300 m and 250 m in Figure 2-3, and 250 m and 250 m in Figure 2-5. Of course, these observed σ_y 's must be recognized as lower limits in about half of the cases, when the plume touched the outer edge of the monitoring arc.

It is concluded that the current OCD/3.0 σ_y predictions are reasonable for the data at a distance of about 1 km in the Carpinteria experiment, as long as the default formula $i_y = (0.5 \text{ m/s})/u(\text{m/s})$ is used for all stabilities. We emphasize that this conclusion is valid only for the distances covered by the tracer data.

2.3 Tests of An Empirical Formula for the Height of the Coastal Internal Boundary Layer

The purpose of this section is to provide additional data to support the empirical formula for the daytime coastal or thermal internal boundary layer (TIBL) height, h_T , used by the OCD/3.0 model. In recent issues of the journal Boundary Layer Meteorology Stunder and Sethuraman (1985) have tested several theoretical and empirical formulas for the TIBL height, and Venkatram (1986) has presented a physical framework for the description of the TIBL height, h_T . He suggested a generalized theoretical equation for h_T , but pointed out that more work is needed to better define the parameters in the equation. The underlying physical principle is that the heat added to the boundary layer as it flows over the land

Observed vs. Predicted Sigma-y Values

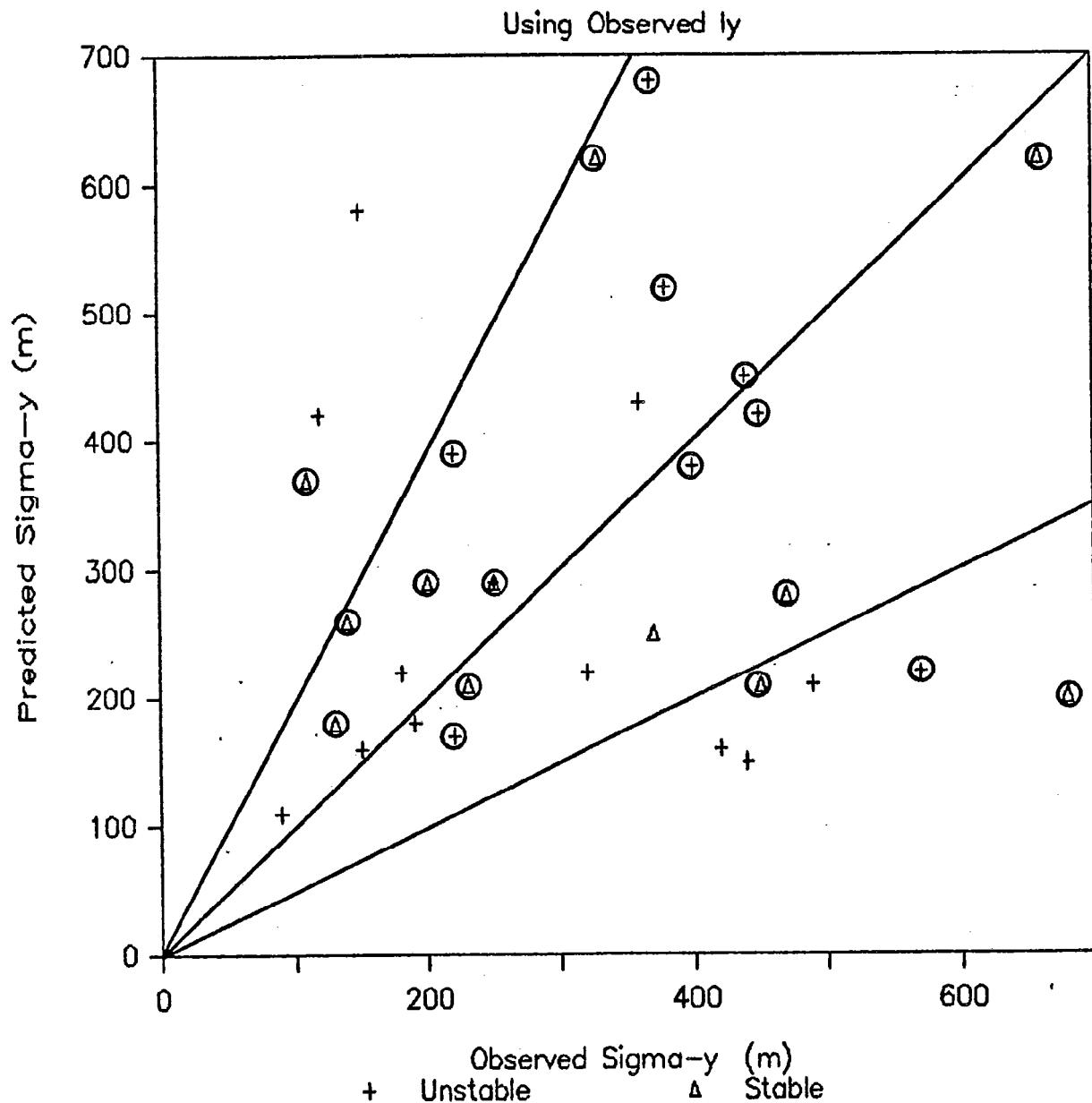


Figure 2-3. Observed Versus Predicted σ_y Values at Carpinteria Using Observed i_y . (The Circled Points Indicate that the Observed Concentrations are on the Edge of the Network and σ_{y0} is an Underestimate).

Observed vs. Predicted Sigma-y Values

Using Predicted i_y (.5/u Stable Cases)

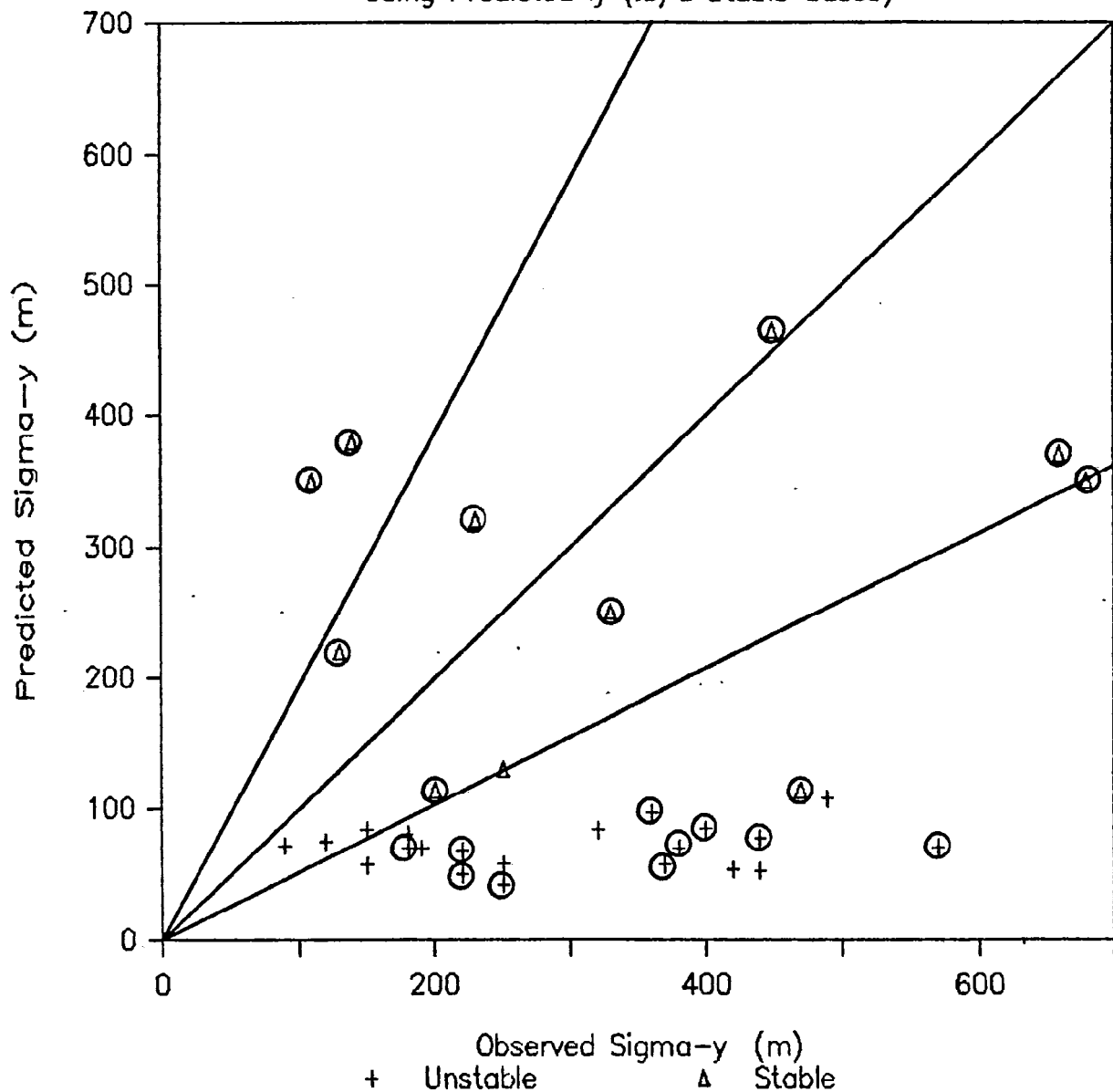


Figure 2-4. Observed Versus Predicted σ_y Values at Carpinteria Using Predicted i_y and Method 1. (The Circled Points Indicate that the Observed Concentrations are on the Edge of the Network and σ_{y0} is an Underestimate).

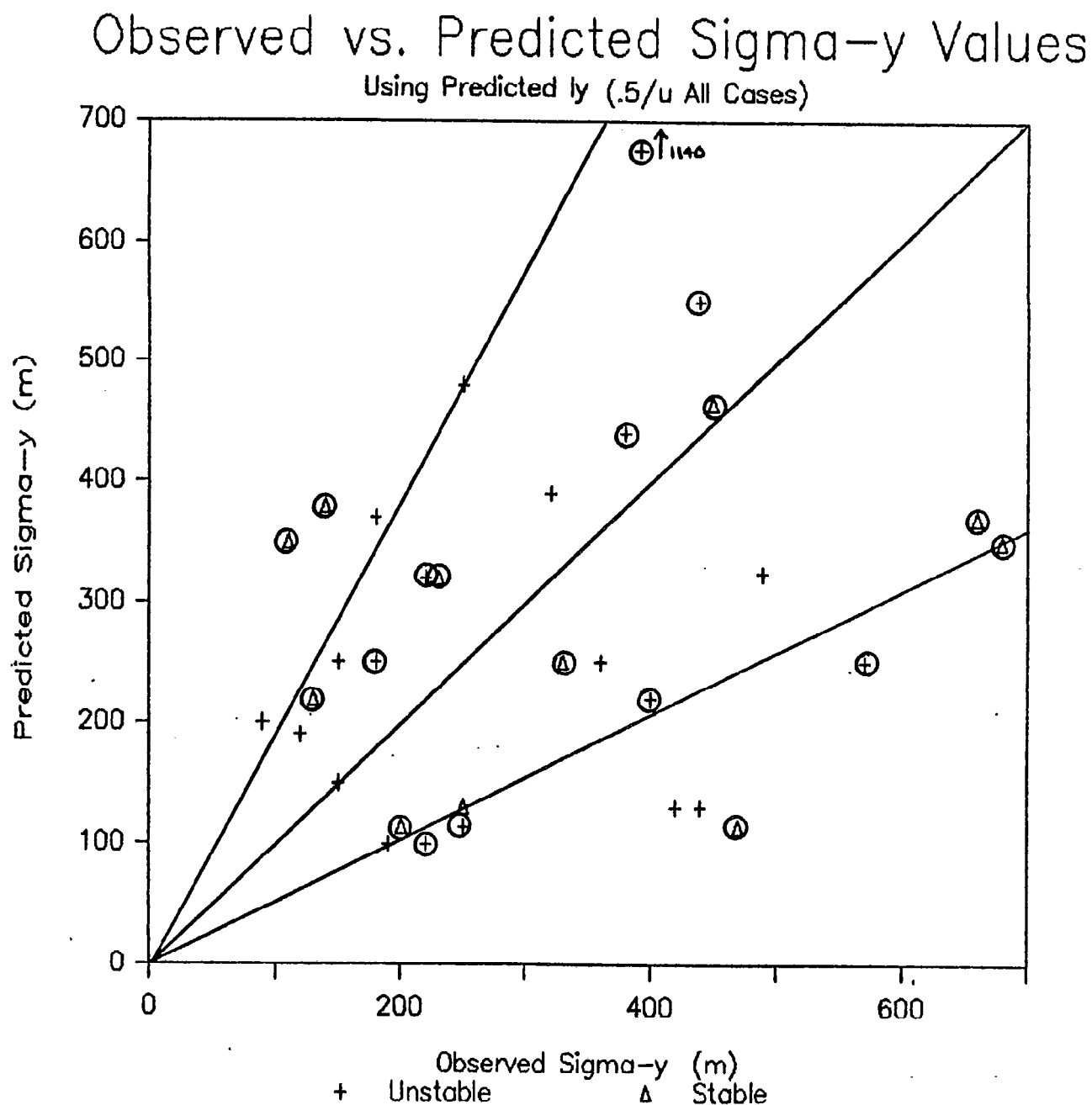


Figure 2-5. Observed Versus Predicted σ_y Values at Carpinteria Using Predicted i_y and Method 2. (The Circled Points Indicate that the Observed Concentrations are on the Edge of the Network and σ_{y0} is an Underestimate).

is used to warm the air and form an adiabatic layer at the base of the initial stable overwater temperature profile. However, it is difficult to estimate the magnitude of the surface heat flux. Data on the overwater temperature profile are hardly every available.

In the original development of the OCD/3.0 model in 1983, a search was conducted for an equation for h_T that would be theoretically correct, would agree with available data, and would be capable of producing reasonable predictions for all hours of the year. Like the EPA regulatory models, the OCD model was intended to be applied to a year or more of hourly data. Several of the formulas mentioned by Stunder and Sethuraman (1985) were tested, with the result that they tended to produce reasonable results for a limited range of conditions, but tended to "blow up" (i.e., produce very small or very large values of h_T) during some hours. For example, if the overwater potential temperature gradient approaches zero, the TIBL height prediction becomes very large. Similarly, if the overland sensible heat flux is small, the TIBL height prediction is very small. It was concluded that these models were not robust, since they permitted large variations in the value of h_T and were quite sensitive to uncertainties in input parameters such as the overwater potential temperature gradient.

It was discovered during the course of that investigation that many of the available data could be fit by a model that permits no variation in h_T with meteorological conditions at a given downwind distance. The OCD/3.0 model uses the following formulas for the daytime TIBL height:

$$h_T = 0.1x \quad (x \leq 2000 \text{ m}) \quad (2-1)$$

$$h_T = 200\text{m} + 0.03 (x-2000\text{m}) \quad (x > 2000 \text{ m}) \quad (2-2)$$

where x is the distance from the shoreline. This TIBL height "model" is presented with no theoretical justification, and it should be recognized by the reader that it is purely empirical.

More recent data from Australia (Rayner, 1987) further justify this TIBL height assumption, as shown in Figure 2-6, which summarizes data from three coastal experiments at widely scattered locations:

Long Island, NY (BNL)	Raynor et al. (1979)
Lake Erie, Ontario (Nanticoke)	Kerman et al. (1982)
Bunbury, Australia	Rayner (1987)

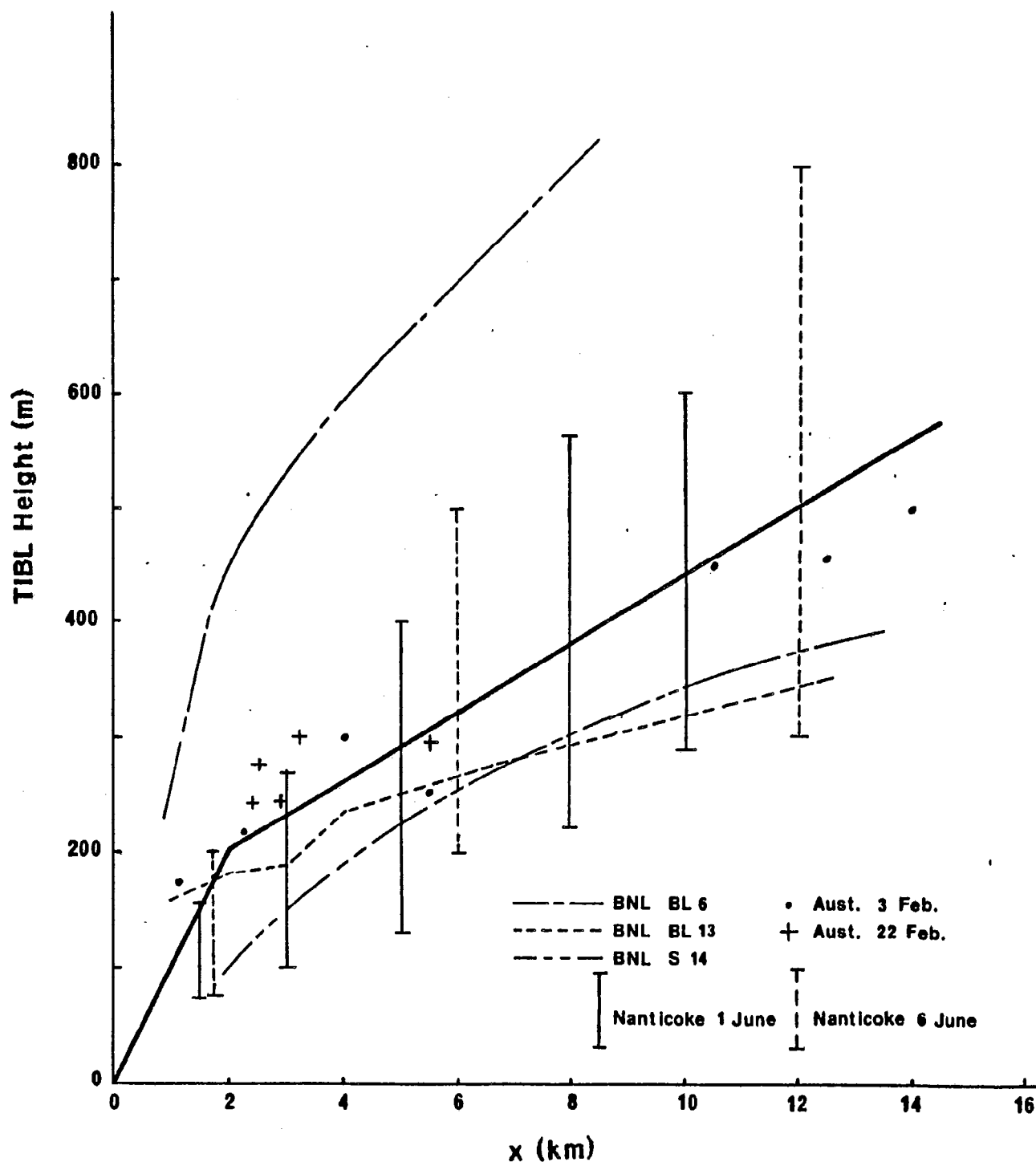


Figure 2-6. Empirical formula for TIBL height (thick solid line) plotted along with observations from a number of field studies. BNL data are from Raynor et al. (1979), Nanticoke data are from Kerman et al. (1982), and Australian data are from Rayner (1987).

It is seen that the robust model given by equation (2-1) passes through the middle of the data, and that most of the data are within a factor of two of the prediction. The new Australian data are in very good agreement ($\pm 20\%$) with the curve at distances ranging from 1 to 14 km. The data from the BNL BL6 experiment are consistently a factor of two above the predicted curve, but are said to be associated with vigorous convection over Long Island (Raynor et al. 1979). Perhaps a future modification to this curve could account for the slight variability of h_T with intensity of overland convection or with wind speed.

It is concluded that there is no reason to change the TIBL height formula in the OCD/3.0 model.

2.4 Summary of Analyses

Several analyses of experimental data at Carpinteria and elsewhere were carried out in order to provide a basis for modifying the OCD/3.0 model. Some of the more interesting results have been presented in this section and are summarized below:

- The wind direction fluctuations at Carpinteria are found to have a non-Gaussian distribution with relatively wide tails. However, if the observed pdf of wind directions is used in the OCD model, there is no improvement in the predictions. It is concluded that the Gaussian assumption can be retained.
- Observed σ_y and OCD/3.0 model predicted σ_y agree fairly well at a downwind distance of one kilometer at Carpinteria. If σ_θ or lateral turbulence intensities i_y are not observed, then the i_y parameterization scheme in OCD/3.0 should be changed so that $i_y = (0.5 \text{ m/s})/u$ for all stabilities.
- The empirical TIBL height formula in the OCD/3.0 model was further justified by an evaluation using a new data set from Australia.

3. OCD/API Model Components

The original OCD/3.0 model code was used as a basis for development of the OCD/API model code. Several changes were made to the code, and these changes all fall into one of three categories:

- Technical improvements with specific justification.
- Technical improvements with no specific justification.
- Improvements made to correct logical errors or reduce model running time.

This section describes the major changes made to the code. There were numerous other minor changes made to improve efficiency and logic procedures that are not mentioned here. The subsections are ordered into the three categories listed above.

3.1 Platform Downwash Algorithm

The OCD/3.0 code accounts for platform downwash using formulas from the BLP model. These formulas were derived for on-land buildings which have bases at ground level. The oil or gas platform, on the other hand, sits on stilts at a height of about 20 m above the water surface. To correct this problem, the API sponsored a series of wind tunnel tests of the flow and dispersion around model oil platforms, from which empirical formulas for dispersion enhancement were derived by Petersen (1986). These formulas were used as a basis for developing a new platform downwash algorithm in the OCD/API code. This change thus falls under the category of technical improvements with specific justification. Some additional work was required so that the formulas covered the following conditions:

- All stabilities.
- All values of H_e/H_b , where H_e is effective plume height and H_b is building height.
- Inclusion of initial σ_y and σ_z by quadratic summation.

The new formulas in the OCD/API code for the initial dispersion parameters σ_{y0}' and σ_{z0}' , which as stated above are modifications to formulas suggested by Petersen (1986), are given below:

$$\sigma_{y0}' = 0.071 \times (A_y + B_y (x/L_y) C_y - 1)^{1/2} \quad (3-1)$$

$$\sigma_{zo}' = 0.11 \times 0.81 (A_z + B_z (x/L_z) C_z - 1)^{1/2} \quad (3-2)$$

where

$$\begin{array}{llll} A_y = 1.9 & B_y = 48.2 & L_y = W/2 & C_y = -1.4 \\ A_z = 3.0 & B_z = 40.2 & L_z = H_b & C_z = -1.4 \end{array}$$

The parameter W is platform width in meters, H_b is total platform height above water surface in meters, and x is the downwind distance in meters. Equations (3-1) and (3-2) are valid for $2.2 < x/H_b < 12.6$. For x/H_b less than 2.2, use the solutions at 2.2, and for x/H_b greater than 12.6, use the solutions at 12.6.

If H_e is the effective height of the plume (stack height plus plume rise), then the effective "initial plume size" used by the OCD/API model at various heights above the oil platform can be calculated as follows:

$$H_e/H_b \leq 1 \quad \sigma_{yo} = \sigma_{yo}' \quad (3-3)$$

$$\sigma_{zo} = \sigma_{zo}' \quad (3-4)$$

$$1.0 < H_e/H_b \leq 1.2 \quad \sigma_{yo} = 0.5 (6 - 5 H_e/H_b) \sigma_{yo}' \quad (3-5)$$

$$\sigma_{zo} = 0.5 (3 - H_e/H_b) \sigma_{zo}' \quad (3-6)$$

$$1.2 < H_e/H_b \leq 3.0 \quad \sigma_{yo} = 0 \quad (3-7)$$

$$\sigma_{zo} = 0.5 (3 - H_e/H_b) \sigma_{zo}' \quad (3-8)$$

$$H_e/H_b > 3.0 \quad \sigma_{yo} = \sigma_{zo} = 0 \quad (3-9)$$

It is difficult to evaluate these new platform downwash formulas with the tracer data from the field experiments, since many of the field experiments used boats or tethersondes for tracer releases. In the case of the few experiments that used a platform for tracer releases, the sampling instruments were several kilometers from the platform, where the component of dispersion due to platform downwash is a minor perturbation to the total plume spread. The sampling instrument should be located within about 200m of the tower to permit satisfactory testing of the new formulas in the OCD/API code.

3.2 Thermal Internal Boundary Layer (TIBL)

The thermal internal boundary layer (TIBL) is formed when stable air flows from the water over the heated land surface. As shown in Section 2.4, the TIBL formula used in OCD/3.0 has been verified by additional data. However there were two significant changes made to the TIBL algorithm:

- Off Centerline Receptors

The OCD/3.0 model used a peculiar procedure for calculating the distance from the shoreline to the receptor. As seen in Figure 3-1a, this distance was assumed to equal the distance from the receptor to the point where the plume centerline crosses the shoreline. For receptors near the centerline, this assumption had little effect. But for some shoreline geometries and receptor positions, this assumption would lead to a very unrealistic number for this distance. In reality, plume material follows more of a straight-line path from source to receptor (Gifford 1968), as shown in Figure 3-1b. Thus the new OCD/API model calculates the TIBL distance using the geometry in Figure 3-1b.

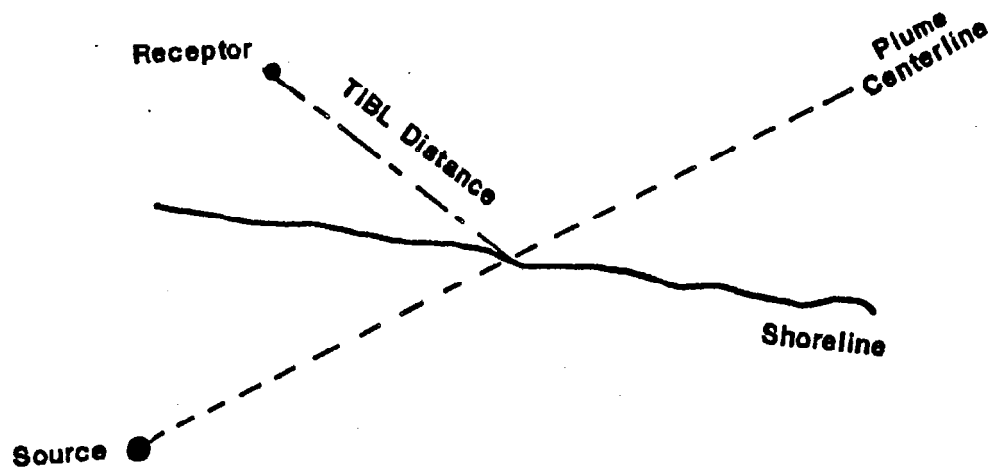
● TIBL Height over Terrain

There are no observations of TIBL height over coastal areas with complex terrain. This would require detailed experiments with tethersondes, lidars, or aircraft, in which temperature or turbulence were measured over a two-dimensional plane extending to heights of about 1 km and to inland distances of about 10 km. Consequently, there are no observational or theoretical justifications for the relatively complex assumptions in OCD/3.0 concerning this variable. For example, the OCD/3.0 model assumes that the growth of the TIBL height is reduced by 50% as steep terrain is encountered. In the OCD/API model, the simplest assumption is made that the TIBL is terrain-following; i.e., the TIBL height above the local terrain at a given distance inland equals that over flat terrain at the same distance inland. There are no scientific reasons to refute this assumption, and it will be retained until data prove otherwise.

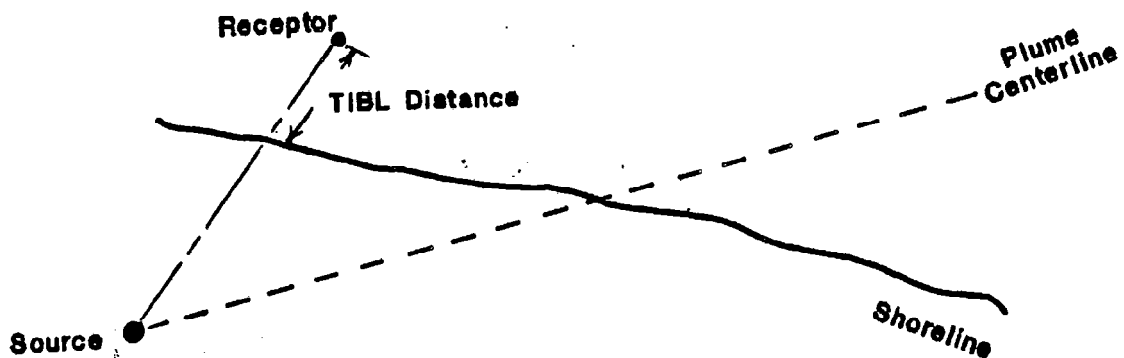
3.3 Fumigation

The OCD/3.0 model contains two alternative methods for calculating fumigation (i.e. vertical dispersion after the plume passes through the TIBL); one method involves the Deardorff and Willis (1982) fumigation algorithm, which is based on observations of mixed layer growth in a laboratory convection tank. After testing this empirical algorithm in several specific real-world applications, it was discovered that the TIBL slopes for which the model was derived were usually less than those that would occur in most coastal areas. Consequently the OCD/API model eliminates this option.

The other alternative method for calculating fumigation in the OCD/3.0 model is a virtual source method, where the vertical dispersion over land proceeds as if the atmosphere is unstable. But a virtual source distance is calculated as the distance upwind



- a. OCD/3.0 Geometry. The TIBL Distance is assumed to equal the distance from the receptor to the point where the plume centerline crosses the shoreline.



- b. OCD/API Geometry. The TIBL Distance is assumed to equal the distance from the receptor to the shoreline along a straight line from the receptor to the source.

Figure 3-1. Change in TIBL Distance Calculation Procedure. This distance is used by the models to estimate the TIBL height.

from the point of TIBL intersection where the source would be if an unstable dispersion rate were present in the overwater atmosphere, and σ_z had its given value at the point of TIBL intersection.

Part of the Carpinteria experiment was specifically intended to evaluate the fumigation component of the model. Tracer gas was released at a height of about 100 m on mornings when a convective mixed layer was expected to develop over land. It appears that the OCD/3.0 model with its virtual source assumption is underpredicting these data, as is shown in Table 3-1. The maximum is underpredicted by a factor of three and the median is underpredicted by about 30%. Using guidance from an analysis by Stunder and Sethuraman (1985) of fumigation models, we tested a variation of the simple Turner (1969) formula and discovered that it produced better agreement. This formula assumes that after the plume centerline intersects the TIBL it is uniformly mixed vertically between the surface and the mixing depth h_T . This model slightly overpredicts (by about 5%) the median of the Carpinteria fumigation data, and slightly underpredicts (by about 37%) the maximum (see Table 3-1). The model currently uses the maximum of concentrations predicted by (1) the Turner complete vertical mixing assumption and (2) the OCD/3.0 virtual source assumption. This procedure involving the maxima is necessary for plume sources near the ground, where vertical plume growth in the overland boundary layer is governed by ambient turbulence rather than TIBL growth (see Figure 3-2). In the top part of the figure, where the plume elevation is high, the Turner assumption will produce the maximum predicted concentration, since it brings the plume to the ground faster. In the bottom part of the figure, where the plume is near the ground, the virtual source assumption will produce the maximum predicted concentration, since it predicts less vertical dispersion.

3.4 Dispersion Coefficients

The OCD/API model incorporates improvements to algorithms for the dispersion coefficients σ_y and σ_z . A few of these improvements are based on specific comparisons with the Carpinteria data, but most are based on recent findings reported by other researchers.

Lateral Dispersion σ_y

Lateral turbulence and dispersion are related through the formula:

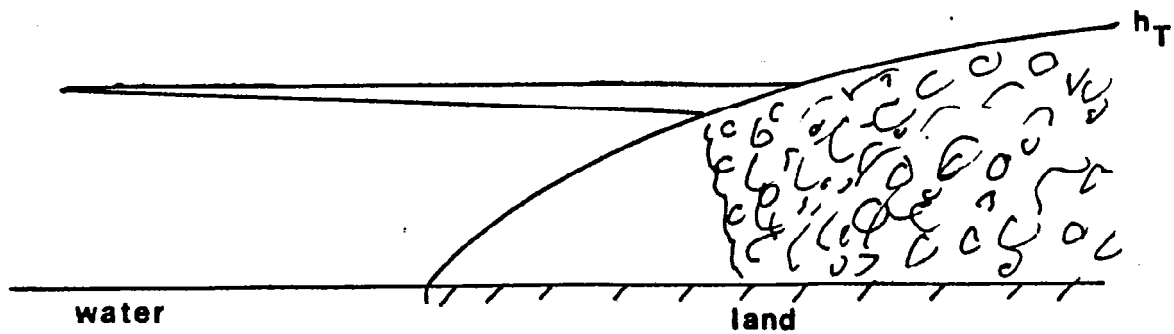
$$\sigma_y = i_y \times f_y (x) \quad (3-10)$$

The OCD/3.0 model uses the Briggs f_y equation, but a comprehensive study by Irwin (1983) suggests that the Draxler (1976) equation agrees better with available data. The Draxler f_y yields a σ_y that is about 30% smaller than the Briggs' σ_y at a downwind distance of about 10 km. The new f_y formula used in the OCD/API model is given below:

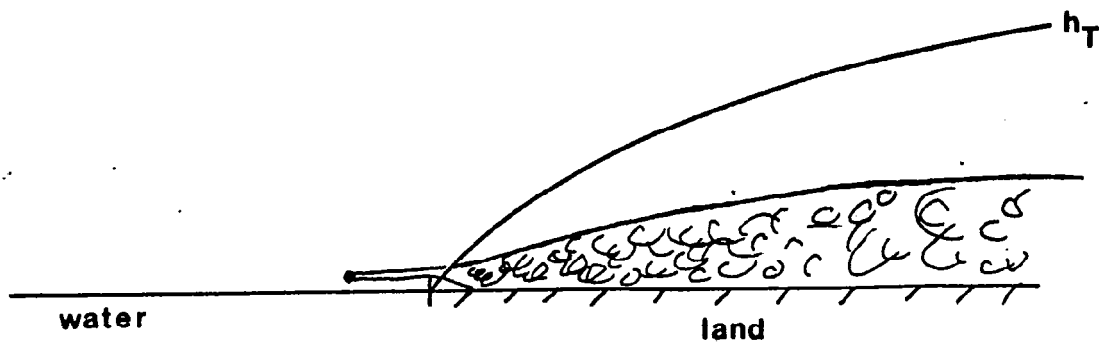
TABLE 3-1

Observed and Predicted Concentrations during Carpinteria Fumigation Experiments. Observed Lateral Turbulence is used for both Model Predictions.

RUN	TIME	MAX C/O ($\mu\text{S}/\text{m}^3$)		
		OBSERVED	OCD/3.0	Turner
9	10:00	4.5	3.2	5.0
11	11:00	4.6	3.2	8.4
12	10:00	8.9	4.5	9.6
12	10:30	4.5	0.0	0.0
12	11:00	15.2	2.4	1.6
13	10:00	11.6	4.0	1.6
13	10:30	4.4	1.4	4.4
13	11:00	2.7	4.9	8.7
Overall Maximum		15.2	4.9	9.6
Median		4.5	3.2	4.7



Turner Complete Vertical Mixing Assumption for Elevated Plumes (Gives Maximum for Plumes Located Far from the Ground).



Virtual Source Assumptions for Low Level Plumes (Gives Maximum for Plumes Located Close to the Ground).

Figure 3-2. Schematic Diagram of Alternate Scenarios Used to Calculate Fumigation.

$$f_y(x) = (1 + 0.9 (x/UT)^{1/2})^{-1} \quad (3-11)$$

where u is wind speed at the elevation of the plume centerline and T is a time scale equal to 1000s.

The OCD/3.0 and OCD/API versions both can use observed lateral turbulence intensity, i_y , if available. However, the default assumptions for i_y have changed in the OCD/API model, based on the analysis of Carpinteria data described in Section 2.2. Figures 2-4 and 2-5 show that the formula,

$$i_y = (0.5 \text{ m/s})/u \quad (3-12)$$

is valid for all stability classes and for plumes above the mixing depth. In the OCD/3.0 model, this formula was used only for stable conditions and for plumes below the mixing depth. The OCD/API model uses Equation (3-12) for all conditions.

Vertical Dispersion σ_z

In the absence of vertical profiles of tracer concentration, formulas for σ_z cannot be directly evaluated. Their evaluation is usually conducted implicitly through analysis of observed ground level concentration patterns. However, in this case, other parameters such as the plume rise and the mixing depth also strongly influence the ground level concentration but are not usually observed directly. The authors know of no offshore or coastal experiments in which all of these parameters have been observed. On the basis of analyses of ground level concentrations, the following changes to the OCD vertical dispersion procedures were made:

- The use of observed vertical turbulence intensity, i_z , is not recommended, since experience by a wide variety of users (e.g. Dugway Proving Ground and Electric Power Research Institute) has shown that these data are highly uncertain (especially for stable conditions).
- The default value of overwater i_z for neutral and unstable conditions is assumed to equal $(0.2 \text{ m/s})/u(\text{m/s})$, which is the median value of i_z observed at Carpinteria for those stabilities.
- The stability class D f_z formula is used for overwater dispersion if the overwater stability class equals A, B, C, or D. This assumption reflects the fact that vertical dispersion is less intense over water than land, and can be approximated by the vertical shape factor appropriate for neutral conditions.

- The "trigger" for stability class G is changed from $d\theta/dz \geq 0.05^\circ\text{C/m}$ to 0.04°C/m . This change provides better agreement with data from very stable conditions at the seven experiment sites analyzed by Hanna et al. (1984). It was found that several of the observed data runs were in the range from 0.04 to 0.05°C/m , and if the trigger was shifted slightly, many more data would fall into class G. Vertical dispersion was observed to be very slight for those runs.

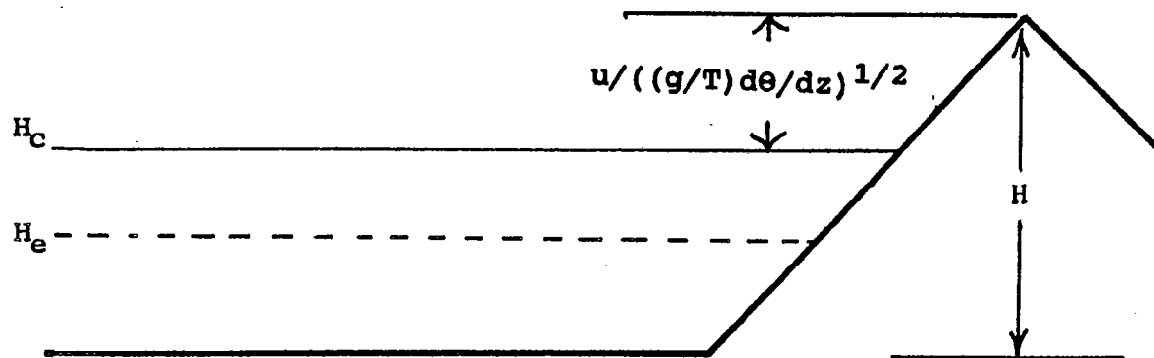
All these σ_z changes in the OCD/API model fall into the category of "technical improvements with no specific justification." They make sense based on our knowledge of the meteorological data and of the basic scientific principles of vertical turbulence and dispersion. However, as pointed out earlier, the vertical term in the dispersion equation also involves the mixing depth, the plume elevation, and fumigation rate. If vertical data from field experiments become available, the OCD/API algorithms can be tested and possibly further improved.

3.5 Critical Streamline Height in Complex Terrain

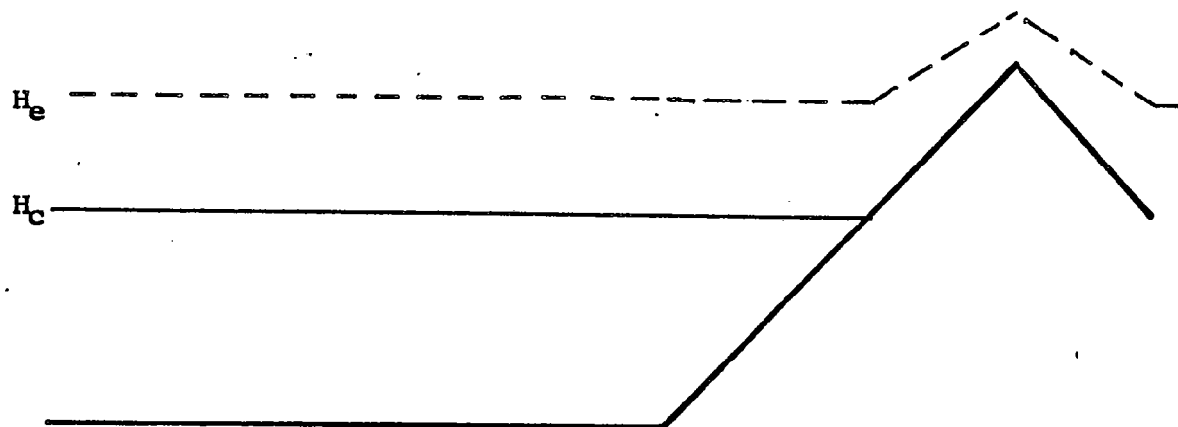
The OCD/3.0 model treats diffusion in complex terrain in a similar manner as the EPA models COMPLEX I and II, which employ an empirical assumption for the lifting of the plume centerline. The OCD/API version uses an improved method to calculate deflection around or over terrain. This procedure is not based on specific observations in coastal zones but is taken from recent theories and observations of transport over simple hill shapes. Much theoretical, laboratory, and field research over the past few years supports the use of the concept of the critical streamline height (Snyder et al. 1985). Given the hill height, H , the wind speed, u , and the temperature gradient at plume height, $d\theta/dz$, a critical streamline height, H_c , is calculated:

$$H_c = H - u / ((g/T)d\theta/dz)^{1/2} \quad (3-13)$$

If the initial plume elevation, H_e , is below H_c , then no lifting of the plume is assumed to occur and the plume path coefficient (PPC) equals 0. The plume path coefficient (PPC), which varies from 0.0 to 1.0, describes the relative amount of vertical deflection of the plume centerline by the terrain. Consequently, the plume experiences no vertical deflection if $\text{PPC}=0.0$ and is "terrain following" if $\text{PPC}=1.0$. These parameters are drawn in Figure 3-3a. If H_e is above H_c , then PPC equals 0.5 and partial lifting of the



a) $H_e < H_c$: No Vertical Deflection of the Plume (PPC=0.0).



b) $H_e \geq H_c$: Vertical Deflection of the Plume, Assuming PPC = 0.5, referred to H_c .

Figure 3-3. Plume Deflection Near Terrain, as Assumed in the OCD/API Model. H_e = Plume Elevation; H = Hill Height; H_c = Critical Streamline Height.

plume occurs (see Figure 3-3b). This lifting is calculated with respect to H_C rather than with respect to the ground surface under H_C .

If H_{eo} is the effective plume height over the water, then the $PPC = 0.5$ assumption implies that the actual plume height, H_e , (referred to msl) is given by the formulas:

$$H_e = H(x) + 0.5 (H(x) - H_C) \quad \text{for } (H(x) - H_C) \leq H_{eo} \quad (3-14)$$

$$H_e = H(x) + 0.5 (H_{eo} - H_C) \quad \text{for } (H(x) - H_C) > H_{eo} \quad (3-15)$$

If the temperature gradient, $d\theta/dz$, is not available, the model reverts to the following assumptions:

$PPC = 0$ for overwater stability classes E, F, and G.

$PPC = 0.5$ for overwater stability classes A, B, C, and D.

These PPC conventions are similar to default assumptions in MPTER and COMPLEX I.

3.6 Reflection in Complex Terrain

The OCD/3.0 model contains the RTDM algorithm for calculating reflection from the ground surface in complex terrain. This procedure is quite long since it contains many mathematical procedures and is time-consuming on the computer. The new OCD/API model has greatly simplified this procedure by completely eliminating the old methodology and replacing it with a simple but equivalent procedure from the EPA's TUPOS program (Turner et al. 1986):

- 1) Calculate ground-level concentration C_1 with complete reflection using terrain height and plume path correction factor PPC (i.e., $PPC = 0.5$ for classes A-D, $PPC = 0$ for classes E and F).
- 2) Calculate concentration C_2 with complete reflection using the Gaussian formula with flat terrain at the height rH_e , where H_e is the smaller of H_e and $H - H_e$, and H_e is the initial plume centerline height above the ground surface upstream of the hill and H_i is the mixing depth. The factor r is given in TUPOS by the following formulas:

$$\begin{aligned}
 r &= 2 \text{ for } \sigma_z/H_e \leq 0.71 \\
 r &= 0 \text{ for } \sigma_z/H_e > 1 \\
 r &= 2.01428 - 1.42857 (\sigma_z/H_e) \text{ for } 0.71 < \sigma_z/H_e \leq 0.85 \\
 r &= 2.925 - 2.5 (\sigma_z/H_e) \text{ for } 0.85 < \sigma_z/H_e \leq 0.93 \\
 r &= 5.25 - 5.0 (\sigma_z/H_e) \text{ for } 0.93 < \sigma_z/H_e \leq 0.97 \\
 r &= 13.3333 (1 - \sigma_z/H_e) \text{ for } 0.97 < \sigma_z/H_e \leq 1
 \end{aligned}$$

3) Let concentration $C = \min (C_1, C_2)$

There is no change in the model predictions due to this new procedure, since both methods lead to the same answer. The new procedure requires much less computer time (by several orders of magnitude).

3.7 Mixing Depth

Most coastal regions will show a complex variation of mixing depth, with different values well out to sea and well inland, and a sloping interface layer (TIBL) near the coastline. There are several assumptions that must be made in the model regarding the effective mixing depth for the plume as it passes through this complex region. We emphasize that no data exist to properly study this phenomenon. Since the OCD/3.0 model contained a complex and unjustified method to account for the variation of mixing depth in complex terrain, some changes to the code were made. These changes are made to correct logical errors and are not justified by any observations. It is noted that the mixing depth, h_m , is a very important factor in determining the ground level concentration, since the concentration approaches an inverse proportionality to h_m as mixing proceeds.

Some of the factors important to this problem are shown schematically in Figure 3-4. First consider the plume while it is still overwater:

- a. If $H_e > h_m$, then vertical mixing is assumed to be unlimited
- b. If $H_e < h_m$, then vertical mixing is assumed to be capped or limited by h_m ,

where H_e is the effective plume height and h_m is the marine mixing depth. The unlimited mixing assumption in part a. generally has little effect, since the atmosphere is stable at that elevation and vertical mixing of the plume by turbulence is minimal.

When the plume comes onshore during conditions when the overland stability class is stable, unlimited vertical mixing is assumed. If the overland stability is unstable or neutral, and if the plume centerline trajectory intersects the TIBL (whose height is referred to as h_T), the mixing depth is given by the maximum of the plume top at the point it enters the TIBL and the TIBL height at the location of the receptor:

$$h = \max (H_p + 2 \sigma_z (x_1) - S x_1, h_T (x_2)) \quad (3-16)$$

In the OCD/API model, the plume top is assumed to be located at an elevation of $2\sigma_z$ above H_p , which is the plume centerline height above mean sea level. The parameter x_1 is the distance from the shore to the point of TIBL interception by the plume centerline, x_2 is the distance from the shore to the receptor, and S is the mean slope of the terrain between the shore and the receptor (see Figure 3.4b). Note that the plume height H_p is calculated for these conditions from the formulas

$$H_p = 0.5 H_e + Sx \quad \text{for } z_r > H_e \quad (3-17)$$

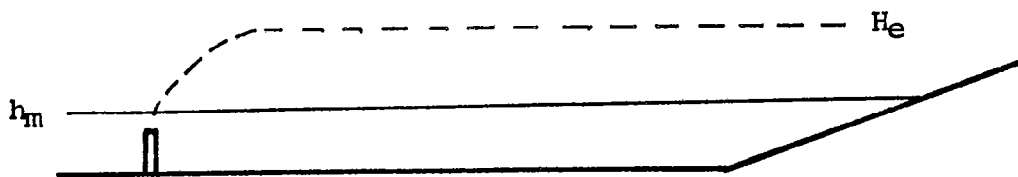
$$H_p = H_e + 0.5 Sx \quad \text{for } z_r \leq H_e \quad (3-18)$$

where z_r is the elevation of the receptor. It is assumed in Equations (3-17) and (3-18) that the "half-height" correction applies over terrain, as used in the EPA's COMPLEX I and II models.

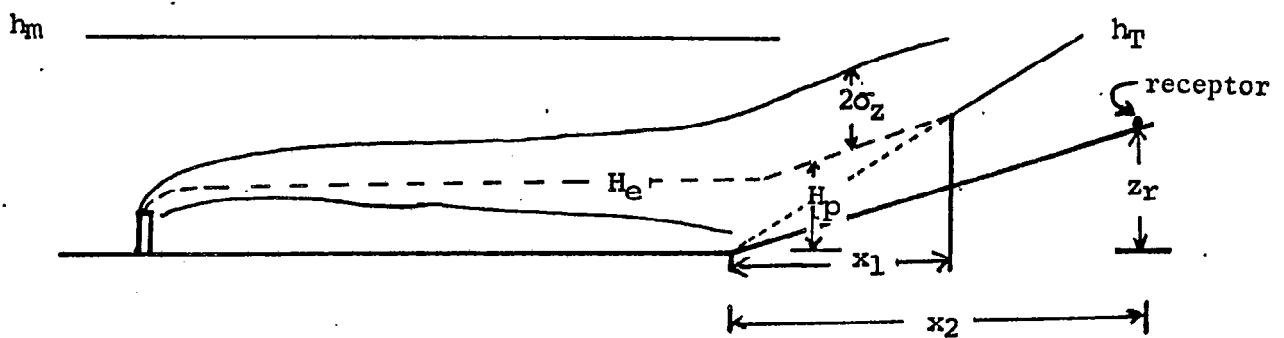
The purpose of the "max" specification in equation (3-16) is to avoid squeezing the plume unrealistically into a shallow layer as it passes through the TIBL, which would violate principles of mass conservation. The revised formulation in OCD/API is an improvement over the OCD/3.0 formulation, which did not account for the plume path correction for terrain or the fact that mixing is effectively unlimited if the plume is in a stable layer. These terms can make a difference of a factor of two or more in the predicted concentrations at the point of maximum ground level concentration.

3.8 Model Input Changes

The sections above give revised equations for several components of the OCD model. In addition, there are many minor coding changes that were made to improve the logic or efficiency of the model. These revisions require minor modifications to the model input parameters for three input cards, as described below.



- a. Stable Overland and $H_e > h_m$ -- Unlimited Mixing is Assumed, Since the Plume is Always in Stable Air.



- b. Not Stable Overland and $H_e \ll h_m$ - Mixing is Limited by Either h_T or $H_p + 2\sigma_z - Sx_1$.

H_e : Plume Centerline Height above Water
 h_m : Marine Mixing Depth
 H_p : Plume Centerline Height above Mean Sea Level
 h_T : TIBL Height above Terrain Surface
 z_r : Receptor Elevation
 S : Terrain Slope

Figure 3-4. Schematic Diagram of Two Mixing Depth Scenarios.

Otherwise, the input is unchanged from that described in the OCD/3.0 Users Guide. Complete input specifications are given in Appendix D, and test cases are given in Appendix E.

If the overwater wind speed is not measured and the overland wind speed u is measured, OCD/3.0 will use a revised wind speed equal to $3u^{2/3}$. This is an empirical formula used to estimate the overwater wind speed when only the overland wind speed is known. However, the OCD/3.0 model uses this formula whether the source is over land or water. For overland sources, the wind speed should obviously not be modified in this way. Therefore, IOPT (24) in OCD Card Type 5 (Main Model Options) has been enabled. For overland sources, IOPT (24) should be set equal to 1 so that wind speeds are not modified. Table 3-2 lists the model options associated with Card Type 5.

The building width used to compute platform downwash using our modifications to Petersen's empirical formulas is input to the model for each source through OCD Card Type 7 (Point Source Description). The building width is input through variable SOURCE (11, NPT) where NPT is the number of point sources. Table 3-3 lists the variables and formats associated with Card Type 7.

The maximum terrain elevation along the line from the source to the receptor is input through variable HTER in Card Type 12 (Discrete Receptor Locations) for each receptor. This terrain elevation (H in Equation 3-13) is used to calculate the critical dividing streamline height (H_c). Table 3-4 lists the variables and formats associated with Card Type 12. If the polar coordinate receptor option is chosen, then the input plume path coefficient PPC as a function of stability is used to calculate deflection over terrain.

3.9 Summary of Changes in OCD/API Code

This section has reviewed the major changes that were made to the OCD/3.0 code in order to create the OCD/API code. These changes range from technical improvements that are justified by field data to logical improvements that are justified by the greatly-reduced running time of the code. The following paragraphs summarize these changes, and Table 3-5 contains a synopsis of the differences between the models.

- Platform Downwash Algorithm - The part of the code that deals with downwash behind the oil platform was modified to include recent results of a wind tunnel study by

Table 3-2

CONTENTS OF OCD CARD TYPE 5*: MAIN MODEL OPTIONS

<u>Variable</u>	<u>Description</u>
IOPT(1)	Use terrain adjustments
IOPT(2)	Do NOT use stack-tip downwash
IOPT(3)	Do NOT use gradual plume rise
IOPT(4)	Use buoyancy-induced dispersion
IOPT(5)	Overland meteorological data is on cards (group 17)
IOPT(6)	Read hourly emissions via unit 15
IOPT(7)	Specify significant sources
IOPT(8)	Input radial distances, generate polar coordinate receptors
IOPT(9)	DELETE emissions with height table
IOPT(10)	DELETE resultant meteorological data summary for averaging period
IOPT(11)	DELETE hourly contributions of significant sources
IOPT(12)	DELETE meteorological data on hourly contributions
IOPT(13)	DELETE case-study printout of plume transport and dispersion on hourly contributions
IOPT(14)	DELETE hourly summary of receptor concentrations
IOPT(15)	DELETE meteorological data on hourly summary
IOPT(16)	DELETE case-study printout of plume transport and dispersion on hourly summary
IOPT(17)	DELETE averaging period contributions
IOPT(18)	DELETE averaging period summary
IOPT(19)	DELETE average concentrations and high-five table for the entire run
IOPT(20)	Disabled (Ignored: use 0)
IOPT(21)	Disabled (Ignored: use 0)
IOPT(22)	Write hourly concentrations to disk or tape (unit 12)
IOPT(23)	Disabled (Ignored: use 0)
IOPT(24)	Land Source (Do Not Modify Wind Speed)
IOPT(25)	Read additional (overwater) meteorological data from unit 13
IOPT(26)	Specify pollutant decay rate
IOPT(27)	Adjust reflection factor for sloping terrain (No effect if IOPT(1) = 0)

*1 line, values entered in free format: 1 = use, 0 = do not use

Table 3-3

Contents of OCD Card Type 7*: Point Source Description

<u>Variable</u>	<u>Format</u>	<u>Columns</u>	<u>Description</u>
RNAME	3A4	1-12	12-character point source name
SOURCE(1, NPT)	F7.3	13-19	x coordinate of stack, user units
SOURCE(2, NPT)	F7.3	20-26	y coordinate of stack, user units
SOURCE(3, NPT)	F7.3	27-33	pollutant emission rate (grams/second)
SOURCE(4, NPT)	F7.3	34-40	height of building or obstacle at or near stack location (meters) relative to platform or water level, depending upon base elevation specified below.
SOURCE(5, NPT)	F7.3	41-47	height of stack-top (m) above ground (if on land), or above platform level (if at sea on "stilts"), or above sea level (if floating on the water)
SOURCE(6, NPT)	F7.3	48-54	stack gas temperature ($^{\circ}$ K)
SOURCE(7, NPT)	F7.3	55-61	stack-top inside diameter (meters)
SOURCE(8, NPT)	F7.3	62-68	stack gas exit velocity (m/sec)
SOURCE(9, NPT)	F7.3	69-75	deviation of stack angle from the vertical (degrees)
ELP (NPT)	F5.0	76-80	elevation of ground, water, or platform base at stack location, relative to the water surface (see text).
SOURCE(11, NPT)	F7.3	81-87	building width used to compute platform downwash (m)

*1 card is input for each stack. The last card contains "ENDP" in columns 1-4.

Table 3-4

Contents of OCD Card Type 12: Discrete Receptor Locations*

<u>Variable</u>	<u>Format</u>	<u>Columns</u>	<u>Description</u>
RNAME	2A4	1-8	8-character receptor name
RREC	F10.3	9-18	x coordinate of receptor, user units
SREC	F10.3	19-28	y coordinate of receptor, user units
ZR	F10.0	29-38	receptor height above local ground level (m)
ELR	F10.0	39-48	ground elevation relative to the water surface at receptor location, user height units
SL	F10.3	49-58	local slope at receptor (used only if IOPT(27) = 1)
SLBASE	F10.0	59-68	elevation at base of slope relative to the water surface
HTER	F10.0	69-78	terrain elevation toward which source to receptor is aligned (used for H_c calculation) (m)

*After the last receptor line (if any), an end delimiter card must be included with "ENDR" in columns 1-4.

Table 3-5

Differences between Algorithm in OCD/3.0 and OCD/API Models

Algorithm	OCD/3.0	OCD/API
Platform Downwash	BLP formulas for ground based buildings.	Petersen formulas for platforms.
TIBL Distance	Receptor to plume center-line shoreline intercept.	Receptor to shoreline intercept along direction to source.
TIBL Height	Reduction over complex terrain based on PPC.	Terrain-following.
Fumigation	Deardorff or virtual source.	Turner (complete mixing) or virtual source.
Lateral Dispersion	Briggs f_y , $i_y = (0.5 \text{ m/s}) / u (\text{m/s})$ stable only.	Draxler f_y $i_y = (0.5 \text{ m/s}) / u (\text{m/s})$ all stabilities.
Vertical Dispersion	f_z given by Briggs curves for the usual stability classes. Class G trigger = 0.05°C/m .	f_z for classes A, B, C, and D given by Briggs curves for D. Class G trigger = 0.04°C/m .
Critical Streamline Height H_c	Not used.	Used as basis for determining PPC.
Reflection over Terrain	RTDM method.	TUPOS method (much faster).
Overland Wind Speed	Equal to overwater wind speed.	Equal to observed overland value.

Petersen (1986). These revised empirical formulas have not yet been adequately tested in the field.

- TIBL - The TIBL procedures were modified to better estimate the distance from the shoreline to the receptor for receptors far off the plume centerline. The TIBL height above the surface of complex terrain is now assumed to be the same as over flat terrain.
- Fumigation - The Deardorff-Willis fumigation algorithm in the OCD/3.0 model was removed and replaced by the Turner (1969) algorithm, which assumes that complete vertical mixing occurs as soon as the plume centerline intercepts the TIBL. The virtual source algorithm was retained as an option in the fumigation calculation.
- Dispersion Coefficients - The Draxler f_y algorithm was substituted for the Briggs algorithm, based on recent comparisons by the EPA (Irwin 1983). The $i_y = (0.5 \text{ m/s})/u(\text{m/s})$ formula is now used for all stabilities in the OCD/API model. Slight modifications were made to stability class criteria to produce more reasonable σ_z estimates (e.g., stability class G is now defined by $d\theta/dz \geq 0.04^\circ\text{C/m}$).
- Critical Streamline Height - The OCD/API model incorporates recent theoretical concepts on the critical streamline height, H_c . Plumes below H_c will impact terrain slopes, while plumes above H_c will rise over the terrain with $\text{PPC} = 0.5$.
- Reflection - The reflection algorithm for complex terrain was greatly simplified by including procedures from the EPA TUPOS model. The answer does not change, but the model runs much faster.
- Mixing Depth - Minor modifications were made to the model to better parameterize the effective mixing depth of the plume at the point it intersects the TIBL.

4. Model Evaluation Procedures and Results

The previous three sections describe the steps that led up to the development of the revised OCD/API model. In this section the OCD/API model is evaluated with tracer data from the Carpinteria field experiment. Comparisons with predictions of the CRSTER/OCS, OCD/3.0, and OCD/CPM models are made. The OCD/CPM model recommended by the EPA for use in California is the same as the OCD/3.0 model, except the COMPLEX I model is used to calculate dispersion once the plume comes onshore. The OCD models were each run twice, once using observed lateral turbulence intensity i_y and once using predicted lateral turbulence intensity. The statistical model evaluation procedures suggested by Hanna and Heinold (1985) were applied to these model predictions.

Maps of the tracer monitoring locations for the Carpinteria field experiment has been given in Figure 1-1. The coastal terrain was moderately steep and the source was close to shore (about 0.5 to 1.5 km).

We emphasize that most of the revisions to the OCD model were made without use of the Carpinteria data. They are based on technical improvements made using material found in the published literature. Consequently this evaluation can be considered to be performed with observations that are independent.

4.1 Description of Models to be Evaluated

The models to be evaluated, the assumptions made, the options implemented, and the meteorological input data sources are listed below.

1) OCD/3.0. The Overwater and Coastal Dispersion (OCD) model Version 3.0 dated January 1986 is run with the following options:

- o Terrain adjustments are considered, including the reflection factor adjustment for sloping terrain.
- o Stack downwash, gradual plume rise, and the initial dispersion due to buoyant plume rise are not considered.
- o Wind direction shear is not included.
- o Sources of meteorological data.

Tethersonde: overwater wind direction, wind speed, mixing depth, vertical temperature gradient, lateral turbulence intensity, and humidity.

Hazel Platform: overwater air temperature, sea-air temperature difference, and vertical turbulence intensity.

Onshore tower: onshore lateral and vertical turbulence intensity.

2) CRSTER/OCS. The CRSTER/OCS model was used by the MMS prior to the development of OCD and is run with the following options:

- o Because CRSTER cannot handle variable receptor locations, MPTER is run instead of CRSTER. To insure equivalence of the two models, the CRSTER wind profile exponents (.10, .15, .20, .25, .30, .30) are used.
- o If stability class is less than 3(C), then stability class is set to 3(C).
- o Terrain adjustments are considered.
- o Stack downwash, gradual plume rise, and the initial buoyant plume are not considered.
- o For receptor heights greater than stack height, receptor heights are set equal to stack height.
- o Meteorology is from the onshore tower.
- o Mixing height equals 500 m.
- o Stability class is determined from local cloud cover and wind speed from the onshore tower.

3) OCD/CPM. The OCD/CPM model is run with the same options as OCD/3.0. This model calculates concentrations differently from OCD if the onshore receptor height is greater than the source height, based on recommendations by EPA Region IX (letter from D. Calkins to J. English dated 20 March 1986). The COMPLEX I model is used once the plume comes onshore for these higher receptors, with appropriate matching of centerline concentrations and σ_z at the shoreline. If all the receptor heights are less than the source height, then the predictions of OCD and OCD/CPM are equal. This hybrid model is recommended by the EPA for use in California.

4) OCD/API. The OCD/API model is run (this is the modified model developed under the current project). It uses the same options and input data described under item (1) above for the OCD/3.0 model.

The differences between OCD/3.0 and OCD/API were documented in Section 3.

Notes: OCD versions/3.0, /CPM, and /API are run using model-calculated vertical turbulence intensities (i.e., observations will not be used). In addition, separate runs are made for a) observed lateral turbulence intensity, and b) model-calculated lateral turbulence intensity. Furthermore, in all cases the wind direction is set equal to the direction from the source to the receptor that shows maximum observed concentration.

4.2 Methods of Model Evaluation

The OCD/3.0, OCD/CPM, OCD/API, and CRSTER/OCS models are evaluated using 37 hours of data from the Carpinteria tracer experiment. Only the maximum observed and predicted concentration are compared for each hour. The model options to be used have been listed in Section 4.1. The four models were run for the 37 hours and predicted normalized concentrations C/Q tabulated for the maximum concentration on each monitoring arc.

The following performance measures are calculated based on the API model evaluation research program (Hanna and Heinold 1985) and recent recommendations by the EPA (Cox and Tikvart 1985):

Maximum C/Q

$$\text{Fractional Mean Bias } FB = (\overline{C_o/Q} - \overline{C_p/Q}) / (0.5(\overline{C_p/Q} + \overline{C_o/Q}))$$

$$\text{Normalized Mean Square Error} = \overline{(C_p/Q - C_o/Q)^2} / (\overline{C_p/Q})(\overline{C_o/Q})$$

Confidence intervals on the fractional mean bias (FB) and the normalized mean square error (NMSE) are estimated using the bootstrap resampling procedure. 95% confidence intervals on the differences in these model performance measures between one model and another are calculated and used to decide whether models are significantly different.

In addition, model behavior is analyzed qualitatively by means of residual plots. Individual residuals, $C_p - C_o$, are plotted as a function of meteorological variables such as wind speed and air-sea temperature difference. A necessary (but not sufficient) condition

for a good model is that the residuals be scattered randomly about zero at all values of the independent variables.

4.3 Results of Model Evaluation

4.3.1 Overall Maximum

The first component of the model evaluation is the investigation of the overall maximum C/Q. Table 4-1 contains the observed and predicted maximum C/Q at Carpinteria. The ratio $(C/Q)_p/(C/Q)_o$ is also given in parentheses following the C_p/Q entry in the table.

Table 4-1

Evaluation of Overall Maximum C/Q at Carpinteria. The Number in Parentheses is the Ratio $(C/Q)_p/(C/Q)_o$.

C/Q Overall Maximum (ns m ⁻³)									
			OCD/API		OCD/3.0		OCD/CPM		CRSTER/
Data Set	n	Obs.	obs. i _y	pre. i _y	obs. i _y	pre. i _y	obs. i _y	pre. i _y	OCS
Carpinteria	37	109,000	132,000 (1.21)	104,000 (0.95)	91,500 (0.84)	317,000 (2.91)	77,700 (0.71)	313,000 (2.87)	32,800 (0.30)

It is seen in the table that the new OCD/API model produces predictions of maximum concentrations that are quite close to the observed maximum at Carpinteria (21% overprediction if observed i_y is used; 5% underprediction if predicted i_y is used). Both the OCD/3.0 and OCD/CPM models underpredict by 16 to 29% if observed i_y is used, and overpredict by a factor of three if predicted i_y is used. The older CRSTER/OCS model underpredicts by a factor of three.

Since the maximum C/Q is a single value, it is inappropriate to discuss confidence intervals for the data in this subsection. The next subsection will cover the FB and NMSE statistics applied to the hourly data for which confidence intervals can be calculated.

4.3.2 Evaluation of Maximum Concentration for Each Hour

The fractional bias $FB = 2 \frac{(\overline{C_p/Q} - \overline{C_o/Q})(\overline{C_p/Q} + \overline{C_o/Q})}{(\overline{C_p/Q} - \overline{C_o/Q})^2}$ and the normalized mean square error $NMSE = \frac{(\overline{C_p/Q} - \overline{C_o/Q})^2}{(\overline{C_p/Q})(\overline{C_o/Q})}$ are calculated using the maximum concentration anywhere on the monitoring network for that hour. 95% confidence limits are calculated using bootstrap resampling for FB for each model, the difference in FB between models, and the difference in NMSE between models. The results are given in Tables 4-2 and 4-3.

Table 4-2

Results of Evaluation of Fractional Bias FB for Maximum C/Q during 37 Hours at Carpinteria. The Models with FB not Significantly Different from 0.0 (at the 95% Confidence Level) are shown. The Model Pairs with Difference in FB not Significantly Different from 0.0 are also shown.

Data Set	Model Number: n	1	2	3	4	5	6	7	Models with FB not sig. diff from 0	Model pairs with Δ FB not sig. diff. from 0
		OCD/API		OCD/3.0		OCD/CPM		CRSTER/ OCS		
		obs. i_y	pre. i_y	obs. i_y	pre. i_y	obs. i_y	pre. i_y			
Carpinteria	37	0.14	0.13	0.46	-0.42	0.58	-0.43	0.63	1,2,4,6	1-2,5-7,4-6, 3-7

Table 4-3

Results of Evaluation of Normalized Mean Square Error NMSE for Maximum C/Q during 37 Hours at Carpinteria. The Model Pairs with Difference in NMSE not Significantly Different from 0.0 (at the 95% Confidence Level) are Shown.

Data Set	Model Number: n	1	2	3	4	5	6	7	Model pairs with Δ NMSE not sig. diff. from 0
		OCD/API		OCD/3.0		OCD/CPM		CRSTER/ OCS	
		obs. i_y	pre. i_y	obs. i_y	pre. i_y	obs. i_y	pre. i_y		
Carpinteria	37	0.70	0.86	1.07	2.59	1.46	2.85	2.62	1-2,1-3,2-3, 3-4,3-6,4-5,4-6, 4-7,5-6

At the Carpinteria site, the new OCD/API model indicates a significantly better fractional bias FB than the other models. The FB values (0.14 for observed i_y and 0.13 for predicted i_y) for the new model are not significantly different from zero (at the 95% confidence level). Similarly, the lowest NMSE at Carpinteria occurs for the OCD/API model options, (0.76 for observed i_y and 0.86 for predicted i_y) although these values are not significantly different from those produced by the OCD/3.0 model with observed i_y .

To allow better visualization of relative model performance, the data in Tables 4-2 and 4-3 are plotted in Figure 4-1. Note that a perfect model would have $FB = NMSE = 0.0$. When maximum concentrations during all 37 hours at Carpinteria are considered, the new OCD/API model (with either observed or predicted i_y) is seen to produce better agreement with observations.

4.4 Residual Analysis

The performance of a good model should not vary with meteorological conditions. If the residuals, in the form of $C_p - C_o$ or C_p/C_o , are plotted versus variables such as wind speed, u , the scatter should be uniform. Examples of residual plots for the OCD/API model at Carpinteria are given in Figures 4-2 and 4-3, where wind speed, u , and air-sea temperature difference, $T_a - T_s$, are used as independent variables. The horizontal lines represent $\pm$ factor of four scatter (outer set of lines), $\pm$ factor of two scatter (lines two and four), and no scatter (inner line). The plotted points show a significant curvature only for the predicted i_y figure with wind speed on the x axis. This can be explained by the fact that predicted i_y is a function of wind speed ($i_y = (0.5 \text{ m/s})/u$), and therefore the model is predicting too small a value for i_y at large wind speeds (leading to too large a prediction of C/Q , since $C \propto \sigma_y^{-1}$). In general about 95% of the predictions are within a factor of ± 4 of the observations, and about 60% of the predictions are within a factor of ± 2 at Carpinteria.

4.5 Summary of Model Evaluation

The OCD/3.0, OCD/CPM, OCD/API and CRSTER/OCS models were tested with data from 37 hours at the Carpinteria site. Emphasis was on the maximum normalized concentration, C/Q , for each period. The following general conclusions were reached:

- The OCD/API model (with observed i_y) was able to best predict the single overall maximum at Carpinteria with a ratio $(C/Q)_p / (C/Q)_o$ of 0.95. The worst model in this regard was CRSTER/OCS, with a median ratio of 0.30.