UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
REGION 10
1200 Sixth Avenue, Suite 900
Seattle, WA 98101-3140

OFFICE OF
ENVIRONMENTAL ASSESSMENT

01 April 2011

MEMORANDUM

SUBJECT: COARE Bulk Flux Algorithm to Generate Hourly Meteorological Data for Use with the AERMOD Dispersion Program; Section 3.2.2.e Alternative Refined Model Demonstration

FROM: Herman Wong
Regional Office Modeling Contact

TO: Tyler Fox
Lead Air Quality Modeling Group

The purpose of this memorandum is to seek Model Clearinghouse concurrence with the Region 10 Office of Environmental Assessment technical staff (R10) decision to approve the Coupled Ocean-Atmosphere Response Experiment (COARE) bulk flux algorithm (FAIRALL et al. 2003) as a meteorological data preprocessor program in the American Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD) system of programs (USEPA 2002) as an alternative refined model for assessing impacts in an Arctic marine ice free environment. Specifically, this model would be used to show compliance with the National Ambient Air Quality Standards (NAAQS) and Prevention of Significant Deterioration (PSD) air quality increments for Shell Offshore Incorporated (SOI) drilling and exploration projects proposing to locate in the Beaufort and Chukchi Seas. Shell's offshore lease blocks are shown in Figures 1 and 2. The approval of an alternative refined model is the responsibility of R10 pursuant to Section 3.0.b and 3.2.2.a in Appendix W of 40 CFR 51 (Appendix W). This model would not just better calculate but give a reasonable estimate of nitrogen dioxide (NO_2) concentration impacts in over water ice free conditions associated with the Arctic environment. To support this approval, R10 reviewed and determined that the materials provided by SOI and its contractors, ENVIRON and/or Air Sciences (collectively, Shell), adequately address the five elements associated with Condition 3 in Section 3.2.2.e of Appendix W for the COARE bulk flux algorithm in AERMOD (AERMOD-COARE) to be an alternative refined model. However, to maintain national consistency, this memorandum seeks your concurrence with R10's approval of AERMOD-COARE.

As you are aware, R10 has been coordinating efforts with Shell since June, 2010 to develop a refined air quality dispersion model that is state of the science for some applications in the Arctic marine environment. These efforts focused on Environmental Protection Agency (Agency) guideline models including the Offshore and Coastal Dispersion (OCD) model (DiCristofaro et al. 1989) and AERMOD, and a non-guideline over water model version of CALPUFF (BOEMRE 2006). After examining the capabilities of each model and what each had to offer, AERMOD was selected because it contains a dispersion program and two data preprocessing programs which can be modified or replaced independent of the other two programs. More importantly, the dispersion program consists of the necessary options and features to estimate air pollutant impacts such as the updated PRIME downwash algorithm (Schulman et al. 2002) and the ability to calculate receptor averaged percentiles associated with the form of the new hourly NAAQS.

The three programs within AERMOD are the dispersion program, the AERMET meteorological data preprocessor program, and the AERMAP terrain preprocessor program. COARE replaces AERMET which was designed to process meteorological data collected at terrestrial locations. Because the water surface is assumed to be flat ($z = 0$), the AERMAP terrain preprocessor program is not used in an over water, ice free air quality modeling analysis.

A. Refined Air Quality Models for a Marine Ice Free Environment

There are two air quality models in the public domain that R10 is aware of to predict concentration impacts in a marine environment. First, there is the Agency recommended OCD model. However, OCD does not contain current science or the options and features necessary to demonstrate compliance with all the NAAQS and air quality increments. Second, there is the non-guideline over water version of CALPUFF released in 2006 by the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE), formerly called the Minerals Management Service (MMS). While CALPUFF does indeed contain the most current science (i.e., COARE), it is not an Agency recommended model to estimate air pollutant concentration impacts in the near field (< 50 kilometers), and it lacks specific options and features to demonstrate compliance with all the NAAQS and air quality increments. Furthermore, CALPUFF does not meet the immediate needs of Shell. However, Shell and R10 views this model as a viable option when there are sufficient Weather Research and Forecasting (WRF) (NCAR 2008) model solutions available that are representative of the outer continental shelf (OCS).

R10 and Shell technical staff started monthly meetings in June 2010 to openly discuss models and modeling options that could be used to conduct a refined ambient air quality impact analysis for a stationary source located inside or seaward of the Beaufort Sea and Chukchi Sea OCS. During the fourth meeting on 09 September 2010, R10 and Shell agreed that the preferred approach would be to use the AERMOD dispersion program with the COARE bulk flux algorithm as a meteorological data preprocessor program (Shell 2010c).

AERMOD is preferred by Shell and R10 because of the following options and features available in the AERMOD dispersion program.

1. The PRIME downwash algorithm is used to evaluate wake effects.
2. The non-guideline Plume Volume Molar Ratio Method (PVMRM) (Hanrahan, P.L. 1999) and Ozone Limiting Method (OLM) (Cole, H.S. et al. 1979) have been coded into the program to estimate 1-hour NO_2 concentration impacts.
3. Output files can be produced to show compliance with the 1-hour NO_2, 1-hour sulfur dioxide (SO_2), and 24-hour particulate matter less than or equal to ten

microns ($PM_{2.5}$) NAAQS.

4. Emission impacts can be predicted for point, area and volume sources.
5. There is a routine that accounts for calm conditions when calculating air pollutant concentrations.
6. The transport of emitted air pollutants is basically a straight line unencumbered by topographic features (i.e., line of sight).
7. AERMOD is maintained and routinely updated by the Model Clearinghouse.

Since COARE replaces AERMET in AERMOD during over water, ice free conditions, this triggers an alternative refined model demonstration under Section 3.0 in Appendix W. The conditions and approval are discussed in the following sections.

B. Regulatory Compliance and Demonstration for Use of an Alternative Refined Model

An alternative refined model can be chosen if it is found more appropriate than the preferred model. Section 3.2.2.b in Appendix W states that “There are three conditions under which such a model may normally be approved for use: (1) If a demonstration can be made that the model produces concentration estimates equivalent to the estimates obtained using a preferred model; (2) if a statistical performance evaluation has been conducted using measured air quality data and the result of that evaluation indicate the alternate model performs better for the given application than a comparable model in Appendix A; or (3) if the preferred model is less appropriate for the specific application, or there is no preferred model.” The R10 authority to accept and approve the use of an alternative refined model is given in Section 3.0.b and 3.2.2.a of Appendix W.

R10 recommended to Shell to use the Condition 1, which was the equivalency demonstration because it was the simplest (Shell 2010c). Section 3.2.2.c in Appendix W states that equivalency “...is established by demonstrating that the maximum or highest, second highest concentrations are within 2 percent of the estimates obtained from the preferred model.” Shell presented the equivalency demonstration results during our 21 October 2010 monthly meeting (Shell 2010e and 2010f). Attachment 1 contains a copy of the equivalency demonstration document. Their conclusion was that OCD and AERMOD-COARE are not equivalent pursuant to Section 3.2.2.c in Appendix W. Nevertheless, Shell stated that AERMOD-COARE is current science and should be pursued under Condition 3 in Section 3.2.2.e in Appendix W since the preferred model is less appropriate (i.e., old science).

Condition 3 contains five elements that must be satisfied before AERMOD-COARE can be found acceptable. They are:

1. The model has received scientific peer review,
2. The model can be demonstrated to be applicable to the problem on a theoretical basis,
3. The data bases which are necessary to perform the analysis are available and adequate,
4. Appropriate performance evaluations of the model have shown that the model is

not biased toward underestimates, and
5. A protocol on methods and procedures to be followed has been established.

During a 09 November 2010 meeting (Shell 2010b), Shell presented its initial evaluation results pertaining to the five elements. This was followed up with a 22 November 2010 conference call between Shell, R10 and the Air Quality Modeling Group (AQMG) within the Office of Air Quality Planning and Standards (OAQPS). Shell refined its results and made another presentation to R10 and AQMG on 28 December 2010. R10 subsequently accepted the results contained in the report entitled "Evaluation of the COARE-AERMOD Alternative Modeling Approach Support for Simulation of Shell Exploratory Drilling Sources in the Beaufort and Chukchi Seas" dated December 2010 (Evaluation Report) (Shell 2010a) for review and acceptance. The review resulted in two information and data request to Shell for clarification, justification and additional analyses (USEPA 2011b and 2011c).

The five elements discussed in Shell's Evaluation Report are summarized below. The complete Evaluation Report with supporting documentation, model input and output files, meeting notes, glossary of terms, and information and data requests with responses have been copied to a CD and found in Attachment 1.

B.1. Element 1: The model has received scientific peer review

The following is an excerpt from Shell's 18 February 2011 response to the R10 Technical Staff AERMOD-COARE Information and Data Request dated 14 February 2011(Shell 2011c).

> "As reflected in the report provided to EPA in December, Shell believes that COARE reflects the most up-to-date science for marine boundary layer conditions. The Coupled Ocean Atmosphere Response Experiment (COARE) began with research in the late 1970s that culminated in the release of the first COARE code in 1993. It has been updated and improved several time since 1993, the current version of the code was released in 2003. It has world-wide acceptance by organizations such as NOAA, the Institute of Atmospheric Physics, CSIRO in Australia, Woods Hole Oceanographic Institute, the French Centre d'Etude des Environments Terrestre et Planetaires and many others. In the ENVIRON report on the evaluation of the COARE-AERMOD method provided to EPA on December 16, 2010, a number of links were provided to reference papers on the topic. For example, one link leads to the following paper:
>
> Brunke, Michael A., Chris W. Fairall, Xubin Zeng, Laurence Eymard, and Judith A. Curry, "Which Bulk Aerodynamic Algorithms are Least Problematic in Computing Ocean Surface Turbulent Fluxes", Journal of Climate, 15 February 2003, pp. 619-635.
>
> This study reports that the COARE algorithm is a preferred method for estimating air mixing in a marine environment. There are many other papers referenced or linked to in the December ENVIRON report that provide a sound scientific basis for the COARE algorithm. We are not stating that it is the only method that could be used, but we have clearly made the required showing that, '[t]he technique has received scientific peer review. ' "

The science behind COARE has been published in scientific peer review journals. Additional information can be found at the following site: http://www.coaps.fsu.edu/COARE/

B.2. Element 2: The model can be demonstrated to be applicable to the problem on a theoretical basis

The developments of the COARE Bulk Air-Sea Flux algorithm are summarized in several papers contained in Attachment 1 and Attachment 2. The following is an excerpt from Shell's 18 February 2011 response to the R10 Technical Staff AERMOD-COARE Information and Data Request dated 14 February 2011 (Shell 2011c).

> "Version 3.0 of the COARE algorithm with journal references and a User's Manual can be accessed at:
>
> ftp://ftp.etl.noaa.gov/users/cfairall/wcrp_wgsf/computer_programs/cor3_0/
>
> and
>
> http://www.coaps.fsu.edu/COARE/flux_algor/
>
> These references provided copies of the code, descriptions of the scientific basis for the code and detailed descriptions on how to use the COARE program. However, Shell acknowledges that COARE was not designed specifically to provide an input file for AERMOD and there are certain steps that must be taken to produce the input files for AERMOD."
>
> "Communication with Ken Richmond of ENVIRON, marine boundary layer experts Dr. Andrey Grachev and Dr. Chris Fairall from NOAA provided the following insight:
>
> From Chris Fairall, 'The original COARE version (2.5) (and the 2003 version (3.0)) was set up so that it could handle water and air temperatures from the tropics to the Arctic. Parameters such as the kinematic viscosity of air have T dependencies. I have listed below a few references to Arctic applications I dug up.' "
>
> "Minimum meteorological variables needed to run the COARE algorithm are the wind speed, the sea surface temperature, the air temperature, and some form of humidity measurement (e.g. relative humidity, absolute humidity, dew point, and wet bulb-temperature). Barometric pressure, precipitation, and a typical mixed layer height are also input variables that can be provided or assigned by COARE default parameters. If options are selected for warm-layer heating and/or cool-skin effects then solar radiation and downward longwave radiation are needed. Shell is not planning to invoke these options but has tested and provided a framework for the provision of these variables using measured solar radiation, cloud cover and ceiling height. COARE also contains several options for the surface roughness length based on wave period and wave height. Shell plans to use the default option that does not need these variables."

A copy of the source code and User's Manual is on the CD in Attachment 1.

B.3. Element 3: The data bases which are necessary to perform the analysis are available and adequate

The performance evaluations of OCD utilized tracer gas experiments from Cameron, Louisiana, and Carpinteria, Pismo Beach and Ventura, California. CALPUFF used the same experiments and added an experiment from Oresund, Denmark/Sweden. In the evaluation of AERMOD-COARE, only the tracer gas experiments from Cameron, Carpinteria and Pismo Beach were used. These three experiments were determined by R10 to be the most representative of atmospheric conditions in the Arctic.

R10 is aware that there are not tracer gas experiments for every geographic region, climatic region, or synoptic region for use in a performance evaluation. That includes the Arctic region. Nonetheless, R10 determined the three tracer gas experiments are acceptable because of the similarity of the tracer gas experiment and marine Arctic sea-surface temperatures and as discussed below.

The following is a passage from Shell's 11 March 2011 response to the R10 Technical Staff AERMOD-COARE Information and Data Request dated 07 March 2011 (Shell 2011b).

> "The selection of experiments to use in the model evaluation was extensively discussed with EPA throughout the fall of 2010. Originally, Shell has selected only the Pismo Beach, CA and Cameron, LA experiments for the evaluation using based on the shoreline, near sea-level location of the receptors. At the specific request of EPA, the Carpinteria, CA experiment was added. Shell suggested at the time that the Carpinteria experiment was not appropriate since the setting involved receptors on a bluff located on the coastline, a setting not seen in the Arctic. The Carpentaria experiment was also more a test of the complex terrain algorithms, not over water dispersion. However, Shell included the Carpinteria experiments at EPA's request. No mention or request was made by EPA at that time to include either the Ventura, CA experiments or the Oresund experiments. The reason for not including the Ventura, CA experiments was that receptors in that case were well inland and no longer reflected the marine environment. The COARE-AERMOD approach is not equipped to simulate changes in the meteorology along the path of the plume. The Oresund experiments were never used in any previous OCD evaluation. They were only used in earlier CALPUFF evaluations. Shell felt that the differences in the use of CALPUFF, principally a long-range transport model, and AERMOD, used for within 50 kilometers, made this comparison less relevant. In addition, the other experiments had already been prepared for OCD and that made it straightforward to adapt them to evaluation with the COARE-AERMOD approach. With the Oresund experiments, the input data were in CALPUFF format and transforming these data to a format for the COARE-AERMOD approach would involve a number of assumptions and judgments that could ultimately impact the results. Shell's concern was that the results of the evaluation could depend on these assumptions and judgments rather than the true model performance."

See ENVIRON communication with Dr. Chris Fairall in the above Section B.2 for appropriateness of COARE in the Arctic marine environment.

B.4. Element 4: Appropriate performance evaluations of the model have shown that the model is not biased toward underestimates.

B.4.a Data Assembly

Data from three tracer gas experiments were used in the performance evaluation. Tables 2, 4 and 6 displays the meteorological data while Tables 3, 5 and 7 identifies the source and receptor data used in the model simulations for Pismo Beach, Cameron, and Carpinteria. Figures 3, 4 and 5 shows the land use and elevation contours at terrestrial locations nearest the three tracer gas experiment release points. These same meteorological tracer source and tracer receptor data were used in the OCD and CALPUFF performance evaluations.

In a 12 March 2011 email (USEPA, 2011a), R10 requested "...Shell to provide a table that list all the meteorological variables required by the AERMOD dispersion program (i.e., surface file and profile file) and how each variable was obtained (e.g., measurement, OCD extracted, independently calculated...etc.) for the three field studies including any passed through variables" to address certain elements under Section 3.2.2.e. Shell's response to the request was three sets of tables (contained in Attachment 3) which provide a "road map" in the meteorological data preparation for the Evaluation study (Shell 2011a). Each table represents one of the three experiments and shows a) input variables to COARE, b) output variables from COARE, and c) the source of the data that make up the surface file and profile file for the five cases shown in Table 1.

Additional discussion is presented in Section 4.2 of the Evaluation Document.

B.4.b Statistical Evaluation Procedures

The following is extracted from Section 4.3 of the Evaluation Document.

"Statistical procedures were applied to evaluate whether the COARE-AERMOD alternative modeling approach was biased towards underestimates using the Pismo Beach, Cameron, and Carpinteria overwater tracer studies. In addition the procedures were applied to examine which of the five cases for preparing the meteorological data performed statistically better within a regulatory modeling framework. The procedures are designed to evaluate how well the modeling approach explains the frequency distribution of the observed concentrations, especially the upper-end or highest observed concentrations. The analysis also measures the model's ability to explain the temporal variability of the observations. Given two unbiased models, the approach with the least amount of scatter would generally be preferred.

The statistical methods and measures are similar to the techniques applied in the EPA evaluation of AERMOD with a few changes as will be discussed below.

- Quantile-quantile (Q-Q) plots were prepared to test the ability of the model predictions to represent the frequency distribution of the observations. Q-Q plots are simple ranked pairings of predicted and observed concentration, such that any rank of the predicted concentration is plotted against the same ranking of the observed concentration. The Q-Q plots can be inspected to examine whether the models are biased towards underestimates at the important upper-end of the frequency distribution

- The robust highest concentration (RHC) has been used in most EPA model evaluation studies to measure the model's ability to characterize the upper end of the frequency distribution. Note that this can also be accomplished by visual inspection of the Q-Q plots. The RHC is calculated from:

  $$RHC = c_n + (\bar{c} - c_n) \ln [(3n-1)/2]$$

  where c_n is the nth highest concentration and c is the average of the (n-1) highest concentrations. Following the suggestions from the EPA AERMOD evaluations, for the small sample data sets in the current analysis n was taken to be 11.

- Log-log scatter diagrams were prepared to test the ability of the model to explain the temporal variability in the observations. When the data from all studies are combined, the combined scatter diagrams can also be used to infer whether the model can explain the variability between the studies.

- Tables of statistical measures and sigma plots were prepared using the BOOT (Level 2/2/2007) statistical model evaluation package. The BOOT program is an update of the package applied in the MMS CALPUFF evaluation. The BOOT program was applied to provide information regarding bias of the mean, scatter or precision, and confidence limits using the bootstrap re-sampling method. The statistics were performed using the natural logarithm of the predictions and observations. Such geometric methods are more appropriate than linear statistics when the data exhibit a log-normal distribution and/or vary over several orders of magnitude. Bias of the geometric mean (MG) is measured from

  $$MG = e^{(\overline{\ln(c_o/c_p}))}$$

  where c_o and c_p are the observed and predicted concentrations, respectively. MG is a symmetric measure that is independent of the magnitude of the concentration where for a perfect model MG = 0 and a factor of two is bounded by $0.5 < MG < 2$. Note there are no zero observed or predicted concentrations in the evaluation data set. The scatter or precision is measured with the geometric variance (VG):"

$$VG = e^{\left(\overline{(\ln(C_o/c_p))^2}\right)}$$

VG is similar to the normalized mean square error in linear statistics and measures scatter about a 1:1 observation-to-prediction ratio. A random scatter of a factor-of-two is equivalent to VG = 1.6, and VG = 12 would indicated a random scatter equivalent to a factor-of-five bias.

The BOOT program also provides other descriptive statistics, including the geometric correlation coefficient and the fraction within a factor-of-two. Importantly, bootstrap re-sampling methods are used by BOOT to test whether differences in MG or VG between the different cases are statistically significant."

B.4.c Results

The following is extracted from Section 5 of the Evaluation Document. Table and figures numbers have been changed to conform to the number system in this document.

"COARE-AERMOD simulations were conducted to predict concentrations from the Pismo Beach, Cameron, and Carpinteria field studies using five different methods for the preparation of the meteorological data and for Case 5 the differences caused by an alternative lateral dispersion term. AERMOD was applied using default dispersion options for rural flat terrain for the Pismo Beach and Cameron simulations. Complex terrain was assumed from the Carpinteria data set. Peak predicted concentrations were compared to peak observed concentrations resulting in a total of 84 paired samples for statistical analysis with the techniques described in Section 4.3. In order to be independent of the tracer emission rate, the simulations were performed with a unit emission rate of 1 g/s and the observations were normalized by the tracer release rate providing concentrations in units of $\mu s/m^3$.

Figure 6 to Figure 10 show log-log scatter diagrams for the five cases. Each plot shows the 1:1 and factor-of-2 bounds for the prediction-to-observation ratio. The scatter diagrams for the five cases are similar with only subtle differences. Most of the differences occur at the upper end of the frequency distribution primarily populated by the Carpinteria complex terrain data set. In this region a couple of the cases over-predict the highest observations. There are also significant differences between the cases for the mid-range concentrations from the Pismo Beach data set, but these differences are difficult to pick out from the scatter diagrams.

Q-Q plots for the combined data set and each of the three individual data sets are shown in Figure 11 to Figure 14. Each plot shows the differences caused by the five different methods used to prepare the meteorological data, and for Case 5 the differences caused by an alternative lateral dispersion term. Figure 15 to Figure 19 show Q-Q plots for each of the five cases where the results from each field studies are compared to one another.

Comparing the Q-Q plots for the combined data set and each of the three field studies, the five COARE-AERMOD simulations generally predict the frequency distribution within a factor-of two. The predictions tend to be biased towards over-prediction for the highest concentrations and under-prediction for the lower-end of the frequency distribution. This tendency is most apparent for the Pismo Beach data set (Figure 10), especially Case 3 where the higher concentrations are over-predicted using the AERMOD σ_Θ estimates. Importantly, COARE-AERMOD does not appear to be biased towards underestimates for the higher end of the frequency distribution, regardless of the options examined in this study.

Comparing the optional cases using the Q-Q plots, there is no clear choice for the best method to prepare the meteorological data. Case 3 using the AERMOD σ_Θ estimates seems to result in over-prediction for the combined data set and each individual data set. Depending on the data set, the method used to estimate the mechanical mixing height influenced the results. The observed mixing height seemed to perform the best for Pismo Beach, while the Venketram estimate worked the best overall. Removing the dependency of the lateral dispersion term on mixing height (Case 5) also seem to improve model performance in some instances, especially the Carpinteria data set where observed mixing heights appear to be the most uncertain.

The BOOT program statistics for each data set are summarized in Table 8 where the best performing modeling approach is highlighted for each statistic and data set. The full output of the BOOT program is attached. Table 8 also shows the RHC calculated for each data set and modeling case. For all the data sets and especially the Pismo Beach data set, the predicted concentrations are more variable than the observations. The Pismo Beach field study had the poorest paired-in-time model performance and the RHC is significantly over-predicted by each modeling alternative. Case 1, Case 3, and Case 5 had the least biased estimates for RHC for the combined, Cameron and Carpinteria data sets, respectively.

Sigma-plots prepared from the BOOT program output are shown in Figure 20 to Figure 23 for the combined data set and each individual data set. Sigma-plots display MG (bias) plotted against VG (scatter). The 95 percent confidence limits on MG are also shown based on the bootstrap re-sampling techniques applied by BOOT. For the combined data set, Case 2 (AERMOD σ_Θ estimates) significantly over-predicts observations and predicts significantly higher than the other cases. Examination of the attached BOOT output listing also suggests Case 5 (Draxler σ_y) has statistically less significant scatter than Case 1, Case 2, or Case 3. For Pismo Beach (Figure 19) this same trend is true, but all the cases have a significant amount of scatter and do not perform as well as for the Cameron or Carpinteria field studies. Comparing Case 3 to Case 4, restricting the Monin-Obukhov length such that Abs (L) > 5 seems to improve performance, but often not in a statistically significant manner.

The Cameron sigma-plot in Figure 22 again shows that Case 2 has the most scatter (highest VG) and the BOOT output suggests these differences are significant at the 95 percent confidence level. All the cases are biased towards over-prediction with Case 3 and Case 4 being the statistically least biased.

The complex terrain field study at Carpinteria is the exception to the trends from the other data sets as shown in Figure 23. Case 2 (AERMOD σ_Θ) predicts significantly higher than the cases with the observed σ_Θ data but in this instance these predictions more closely match observed concentrations. Case 1 is biased towards under-prediction for Carpinteria, but examination of the Q-Q plot and scatter diagram in Figure 6 and Figure 14 shows this Case's performance is relatively good at the upper-end of the observed frequency distribution."

B.5. Element 5: A protocol on methods and procedures io be followed has been established.

On 26 October 2010, Shell provided R10 with a basic protocol to demonstrate AERMOD-COARE as a preferred alternative model under Section 3.2.2.e in Appendix W (Shell 2010d). As the evaluation progressed, R10 requested Shell amplify Elements 3 and 4 to include the Carpinteria, CA tracer gas experiment as well provided Shell with two information and data requests.

C. Conclusions and Recommendations

C.1. Conclusions

R10 has reviewed the technical materials, demonstrations, and evaluations provided by Shell and has determined that each of the five elements contained within Section 3.2.2.e of Appendix W in 40 CFR 51 has been adequately addressed. Furthermore, all five cases show predicted concentrations are not bias toward underestimation. R10 pursuant to Section 3.0.b and 3.2.2.a approves the use of the AERMOD dispersion program with the COARE bulk flux algorithm as an acceptable alternative model to predict near field ambient air pollutant concentration impacts in the Arctic marine ice free environment of the Beaufort and Chukchi Seas.

Approval to use this alternative model is made on a case-by-case basis. Should a project proponent desire to use AERMOD-COARE in an Arctic marine ice free environment air permit project, a request must be made to R10 prior to the submission of an ambient air quality impact analysis with reference to this document and with other technical justifications, particularly with respect to the hourly meteorological data (e.g., mixing heights) to avoid delays in project review and draft air permit issuance (Section 3.0.c in Appendix W). Furthermore, Case 5 is acceptable but will require a modification of the dispersion program to read the sigma values.

As part of the public notice and comment period, R10 will solicit comments on the use of AERMOD-COARE to support the issuance of the draft air permit.

C.2. Recommendations

1. To deal with the difficulties of collecting meteorological data overwater such as in the Arctic or the Gulf of Mexico, the use of predicted meteorology should be evaluated and tested. Currently, there is the Mesoscale Model Interface (MMIF) program that can read WRF and MM5 solutions and re-diagnosis and reformat the meteorological variable data for direct input in the AERMOD dispersion program. If COARE is added to MMIF, the use of measured marine environment meteorology could be eliminated in some applications.

2. While AERMOD-COARE is acceptable to R10 for current application in the Arctic marine ice free environment, it lacks two features found in OCD: platform building downwash algorithm and a shoreline fumigation algorithm. These two features should be coded into the AERMOD dispersion program for wider application in lieu of using OCD.

3. AERMOD-COARE was evaluated with Carpinteria, Pismo Beach and Cameron tracer gas experiments. To make AERMOD-COARE applicable to mid-latitudes and tropics, additional evaluations should be conducted consistent with Section 3.2.2.e in Appendix W of 40 CFR 51 including the use of Ventura and Orelund, Denmark/Sweden tracer gas experiments. The latter experiment was used with CALPUFF.

4. Besides the five tracer gas experiments identified above in Section B.3, a search should be initiated to determine if other tracer gas experiments are available to evaluate AERMOD-COARE, particularly for Arctic conditions.

5. AERMOD-COARE is limited to a downwind distance of 50 kilometers. Consideration should be given to evaluate CALPUFF under Section 3.2.2.e to predicted concentration impacts at distance exceeding 50 kilometers in the Gulf of Mexico and the Arctic.

D. References

BOEMRE (Bureau of Ocean Energy Management, Regulation and Enforcement and formerly the Minerals Management Service (MMS)). 2006. Development of the Next Generation Air Quality Models for Outer Continental Shelf (OCS) Applications, Final Report: Volume 1. January.

Cole, H.S. and J. E. Summerhays. 1979. A Review of Techniques Available for Estimation of Short-Term NO_2 Concentrations. Journal of the Air Pollution Control Association, 29(8): 812-817

DiCristofaro, D.C. and S. R. Hana. 1989. OCD: The Offshore and Coastal Dispersion Model. Volume I: User's Guide. Sigma Research Corporation, Westford, MA.

Fairall, C. W. and E.F. Bradley. 2003. The TOGA-COARE Bulk Air-Sea Flux Algorithm. NOAA/ERL/ETL, 325 Broadway, Boulder, CO. September 2.

Hanrahan, P. L. 1999. The Plume Volume Molar Ratio Method NO_2/NO_x Ratios in Modeling - Part I: Methodology. Journal of the Air & Waste Management Association, 49:1324-1331.

NCAR (National Center for Atmospheric Research). 2008. Weather Research and Forecasting ARW Version 3 Modeling System User's Guide. Mesoscale & Microscale Meteorology Division, Boulder, CO. July.

Schulman L. L., D.G. Strimaitis and J.S. Scire. 2002. Development and evaluation of the PRIME plume rise and building downwash model. Journal of the Air & Waste Management Association.

Shell (Shell Oil Incorporated). 2011a. Email from K. Winges, ENVIRON to H. Wong, EPA Region 10. 14 March.

Shell. 2011b. Email from Kirk Winges, ENVIRON to H. Wong, EPA Region 10. March 11.

Shell. 2011c. Email from Kirk Winges , ENVIRON to H. Wong, EPA Region 10. February 18.

Shell. 2010a. Evaluation of the COARE-AERMOD Alternative Modeling Approach Support for Simulation of Shell Exploratory Drilling Sources In the Beaufort and Chukchi Seas developed by ENVIRON. December.

Shell. 2010b. Shell Beaufort Sea Permit Application Meeting Notes of 09 November. November 10.

Shell. 2010c. Shell Beaufort Sea Permit Application Meeting Notes of 21 October. November 10.

Shell. 2010d. Email from Ken Richmond, ENVIRON to H. Wong, EPA Region 10. October 26

Shell. 2010e. Comparison of OCD vs COARE-AERMOD Support for Simulation of Shell Exploratory Drilling Sources In the Beaufort and Chukchi Seas developed by ENVIRON. October 24.

Shell. 2010f. Shell Beaufort Sea Permit Application Meeting Notes of 09 September. October 22.

USEPA (U.S. Environmental Protection Agency). 2011a. Email from H. Wong, EPA Region 10 to Kirk Winges, ENVIRON. March 12.

USEPA. 2011b. R10 Technical COARE Clarification Request, and Second Information and Data Request. Seattle, WA. March 07.

USEPA. 2011c. R10 Technical Staff AERMOD-COARE Information and Data Request; First Request. Seattle, WA February 14.

USEPA. 2002. AERMOD: Description of Model Formulation. EPA Support No. EPA-454/R-02-002d. Research Triangle Park, NC. April; and Cimorelli, A. et al. 2005. AERMOD: A Dispersion Model for Industrial Source Application, Part I: General Model and Boundary Layer Characterization, Journal of Applied Meteorology, 44(5): 682-693.

Enclosures

cc: Ann Williamson
Mahbubul Islam
Doug Hardesty
Roger Brode
George Bridger

Table 1
Evaluation Cases

Case No.	Summary
1	Require Abs (L) > 5, use measured σ_θ measurements, and use the Venketram equation in AERMET for z_{im} and require z_{im} > 25 m
2	Require Abs (L) > 5, use AERMOD predicted σ_θ, and use the enketram equation in AERMET for z_{im} and require z_{im} > 25 m
3	Require Abs (L) > 1, use measured σ_θ measurements, and observed mixing heights for mechanical mixing height (z_{im})
4	Require Abs (L) > 5, use measured σ_θ measurements, and observed mixing heights for mechanical mixing height (z_{im})
5	Require Abs (L) > 5, use measured σ_θ measurements, use the Venketram equation in AERMET for z_{im} and require z_{im} > 25 m, and modify AERMOD to use Draxler equation for the ambient later dispersion parameter: $\sigma_y = x(\sigma_v / u) / (1 + 0.9(x/1000u)^{0.5})$ where x = downwind distance u = effective wind speed σ_v= effective standard deviation of the lateral wind speed calculated from σ_θ

Table 2 Pismo Beach OCD Meteorological Data

Date/Time	Wind Obs. Ht. (m)	Temp RH Obs. Ht. (m)	Wind Dir.	Wind Speed (m/s)	Mix Ht. (m)	Rel. Humid. (%)	Air Temp. (K)	Air-Sea Temp (K)	Virt. Pot. Temp Grad. (K/m)	Sigma-Theta	Revised Air-Sea Temp (K)
12/8/81 15:00	20.5	7.0	261	2.2	100	67	287.7	1.3	0.030	9.43	1.30
12/8/81 16:00	20.5	7.0	284	1.6	100	75	287.5	1.2	0.030	12.90	1.20
12/11/81 14:00	20.5	7.0	275	4.5	600	74	285.6	-0.4	0.010	5.60	**0.00**
12/11/81 15:00	20.5	7.0	283	5.4	600	73	286.1	0.0	0.010	4.57	**0.00**
12/11/81 17:00	20.5	7.0	289	8.6	700	84	286.0	0.1	0.010	2.12	0.10
12/11/81 19:00	20.5	7.0	305	7.9	900	81	286.1	0.2	0.010	45.00	0.20
12/13/81 14:00	20.5	7.0	289	5.4	50	95	285.5	-0.8	0.000	0.92	-0.80
12/13/81 15:00	20.5	7.0	280	6.1	50	97	285.3	-0.8	0.000	2.41	-0.80
12/13/81 17:00	20.5	7.0	301	7.9	50	92	286.2	0.3	0.060	1.89	**0.35**
12/14/81 13:00	20.5	7.0	292	7.7	50	79	287.2	1.3	0.020	1.20	1.30
12/14/81 15:00	20.5	7.0	292	10.9	50	90	286.4	0.4	0.020	1.20	0.40
12/14/81 17:00	20.5	7.0	296	9.9	50	88	286.7	0.9	0.020	1.78	0.90
12/15/81 13:00	20.5	7.0	304	5.6	50	88	286.1	0.3	0.010	14.41	0.30
12/15/81 14:00	20.5	7.0	299	6.1	50	83	287.7	1.1	0.010	45.00	1.10
12/15/81 19:00	20.5	7.0	321	1.6	50	70	289.4	3.4	0.030	45.00	3.40
6/21/82 15:00	20.5	7.0	276	4.3	800	84	287.5	1.5	0.008	1.37	1.50
6/21/82 16:00	20.5	7.0	269	3.8	800	86	287.3	1.4	0.008	2.12	1.40
6/21/82 17:00	20.5	7.0	261	2.7	800	87	287.3	1.5	0.008	6.84	1.50
6/21/82 18:00	20.5	7.0	276	3.0	800	89	286.9	1.2	0.008	19.70	1.20
6/22/82 15:00	20.5	7.0	274	3.7	700	80	288.6	1.7	0.005	6.05	1.70
6/22/82 16:00	20.5	7.0	268	5.2	700	78	288.8	2.1	0.005	3.32	2.10
6/22/82 19:00	20.5	7.0	289	3.2	700	84	287.2	1.3	0.005	10.59	1.30
6/24/82 13:00	20.5	7.0	269	3.9	600	82	288.1	0.9	0.010	27.79	0.90
6/24/82 15:00	20.5	7.0	269	5.3	600	84	288.1	0.6	0.010	7.46	0.60
6/25/82 12:00	20.5	7.0	286	5.6	100	76	288.9	2.2	0.010	1.37	2.20
6/25/82 13:00	20.5	7.0	280	6.5	100	80	288.5	2.6	0.010	1.60	2.60

Table 2 Pismo Beach OCD Meteorological Data (Continued)

Date/Time	Wind Obs. Ht. (m)	Temp RH Obs. Ht. (m)	Wind Dir.	Wind Speed (m/s)	Mix Ht. (m)	Rel. Humid. (%)	Air Temp. (K)	Air-Sea Temp (K)	Virt. Pot. Temp Grad. (K/m)	Sigma-Theta	Revised Air-Sea Temp (K)
6/25/82 15:00	20.5	7.0	286	9.8	100	82	288.3	2.6	0.010	5.48	2.60
6/25/82 16:00	20.5	7.0	288	9.1	100	82	288.3	2.9	0.010	0.92	2.90
6/25/82 17:00	20.5	7.0	290	9.5	100	81	288.4	3.2	0.010	1.20	3.20
6/27/82 16:00	20.5	7.0	287	12.7	100	93	287.0	3.4	0.010	1.09	3.40
6/27/82 18:00	20.5	7.0	285	10.2	100	94	287.7	3.7	0.010	7.74	3.70

Table 3 Pismo Beach Source and Receptor Data

Date/Time	Rel. Ht.(m)	Bldg. Ht. (m)	Bldg. Wid. (m)	Recep. Dist.(m) [1]
12/8/81 15:00	13.1	7.0	20.0	6730
12/8/81 16:00	13.1	7.0	20.0	6506
12/11/81 14:00	13.1	7.0	20.0	6422
12/11/81 15:00	13.1	7.0	20.0	6509
12/11/81 17:00	13.1	7.0	20.0	6619
12/11/81 19:00	13.1	7.0	20.0	7316
12/13/81 14:00	13.1	7.0	20.0	6516
12/13/81 15:00	13.1	7.0	20.0	6372
12/13/81 17:00	13.1	7.0	20.0	6870
12/14/81 13:00	13.1	7.0	20.0	6378
12/14/81 15:00	13.1	7.0	20.0	6378
12/14/81 17:00	13.1	7.0	20.0	6526
12/15/81 13:00	13.1	7.0	20.0	6944
12/15/81 14:00	13.1	7.0	20.0	6697
12/15/81 19:00	13.1	7.0	20.0	8312
6/21/82 15:00	13.6	7.0	20.0	6532
6/21/82 16:00	13.6	7.0	20.0	6589
6/21/82 17:00	13.6	7.0	20.0	6748
6/21/82 18:00	13.6	7.0	20.0	6532
6/22/82 15:00	13.6	7.0	20.0	6125
6/22/82 16:00	13.6	7.0	20.0	6214
6/22/82 19:00	13.6	7.0	20.0	6054
6/24/82 13:00	13.6	7.0	20.0	6244
6/24/82 15:00	13.6	7.0	20.0	6244
6/25/82 12:00	13.6	7.0	20.0	6406
6/25/82 13:00	13.6	7.0	20.0	6377
6/25/82 15:00	13.6	7.0	20.0	6406
6/25/82 16:00	13.6	7.0	20.0	6435
6/25/82 17:00	13.6	7.0	20.0	6455
6/27/82 16:00	13.6	7.0	20.0	6630
6/27/82 18:00	13.6	7.0	20.0	6579

1. All releases were simulated with a 270 degree wind direction from a source at (0, 0) and a receptor at (X,0) where X is the downwind distance with the peak observed concentration. All receptors are in flat terrain with a 1.5m flag pole height.

Table 4 Cameron OCD Meteorological Data

Date/Time	Wind Obs. Ht. (m)	Temp RH Obs. Ht. (m)	Wind Dir.	Wind Speed (m/s)	Mix Ht. (m)	Rel. Humid. (%)	Air Temp. (K)	Air-Sea Temp (K)	Virt. Pot. Temp Grad. (K/m)	Sigma-Theta	Revised Air-Sea Temp (K)
7/20/81 14:00	10	10	202	4.6	800	63	302.4	-2.7	0.00	6.39	-2.7
7/20/81 15:00	10	10	210	4.8	800	64	302.6	-2.6	0.00	4.92	-2.6
7/23/81 17:00	10	18	232	4.3	225	73	303.6	-1.4	0.00	4.74	-1.4
7/23/81 18:00	10	18	229	5.1	225	74	303.7	-1.2	0.00	4.74	-1.2
7/27/81 20:00	10	18	176	2.1	400	82	300.2	-4.4	0.00	999.00	-4.4
7/27/81 22:00	10	18	151	4.5	450	82	300.0	-4.5	0.00	999.00	-4.5
7/29/81 16:00	10	18	218	4.6	420	69	303.0	-2.2	0.00	9.59	-2.2
7/29/81 17:00	10	18	240	5.0	430	68	303.0	-2.0	0.00	6.45	-2.0
7/29/81 19:00	10	18	241	5.0	450	68	303.1	-1.7	0.00	9.59	-1.7
2/15/82 16:00	10	10	142	5.7	200	89	287.4	0.0	0.06	999.00	**0.5**
2/15/82 17:00	10	10	134	5.6	200	88	287.1	-0.8	0.06	999.00	**0.5**
2/15/82 20:00	10	10	147	5.9	200	87	287.4	-0.4	0.06	999.00	**0.5**
2/17/82 14:00	10	10	178	3.3	200	93	288.8	2.1	0.03	2.46	2.1
2/17/82 15:00	18	18	195	3.7	200	93	288.1	0.9	0.03	7.63	0.9
2/17/82 16:00	18	18	210	4.3	200	93	288.0	0.6	0.03	3.89	**0.4**
2/17/82 17:00	18	18	206	3.5	200	93	287.7	-0.2	0.03	3.78	**0.4**
2/17/82 18:00	18	18	193	3.5	200	93	287.4	-0.7	0.03	2.06	**0.4**
2/22/82 14:00	18	18	171	5.2	100	75	290.6	1.3	0.03	2.69	1.3
2/22/82 16:00	18	18	172	4.7	100	76	290.6	0.9	0.03	2.41	0.9
2/22/82 17:00	18	18	182	4.5	100	76	290.9	0.8	0.03	2.81	0.8
2/23/82 14:00	18	18	152	4.8	50	84	291.5	3.7	0.03	0.63	3.7
2/23/82 17:00	18	18	165	6.2	80	88	291.2	2.3	0.03	3.21	2.3
2/24/82 15:00	18	18	143	3.7	50	49	293.1	5.0	0.05	2.75	5.0
2/24/82 16:00	18	18	143	3.7	50	50	292.9	4.6	0.05	3.21	4.6
2/24/82 17:00	18	18	140	3.5	50	50	292.9	4.7	0.05	3.26	4.7
2/24/82 19:00	18	18	156	4.1	50	52	290.7	2.7	0.05	2.63	2.7

Table 5 Cameron Source and Receptor Data

Date/Time	Rel. Ht.(m)	Bldg. Ht. (m)	Bldg. Wid. (m)	Recep. Dist.(m) [1]
7/20/81 14:00	13.0	0.0	0.0	7180
7/20/81 15:00	13.0	0.0	0.0	7400
7/23/81 17:00	13.0	0.0	0.0	8930
7/23/81 18:00	13.0	0.0	0.0	8710
7/27/81 20:00	13.0	0.0	0.0	7020
7/27/81 22:00	13.0	0.0	0.0	7859
7/29/81 16:00	13.0	0.0	0.0	7820
7/29/81 17:00	13.0	0.0	0.0	9780
7/29/81 19:00	13.0	0.0	0.0	9950
2/15/82 16:00	13.0	7.0	20.0	4834
2/15/82 17:00	13.0	7.0	20.0	5762
2/15/82 20:00	13.0	7.0	20.0	4526
2/17/82 14:00	13.0	0.0	0.0	7000
2/17/82 15:00	13.0	0.0	0.0	6985
2/17/82 16:00	13.0	0.0	0.0	7400
2/17/82 17:00	13.0	0.0	0.0	7260
2/17/82 18:00	13.0	0.0	0.0	6950
2/22/82 14:00	13.0	0.0	0.0	7095
2/22/82 16:00	13.0	0.0	0.0	7070
2/22/82 17:00	13.0	0.0	0.0	6955
2/23/82 14:00	13.0	0.0	0.0	7769
2/23/82 17:00	13.0	0.0	0.0	7245
2/24/82 15:00	13.0	7.0	20.0	5669
2/24/82 16:00	13.0	7.0	20.0	5669
2/24/82 17:00	13.0	7.0	20.0	6023
2/24/82 19:00	13.0	7.0	20.0	4786

1. All releases were simulated with a 270 degree wind direction from a source at (0, 0) and a receptor at (X,0) where X is the downwind distance with the peak observed concentration. All receptors are in flat terrain with a 1.5m flag pole height.

Table 6 Carpinteria OCD Meteorological Data

Date/Time	Wind Obs. Ht. (m)	Temp RH Obs. Ht. (m)	Wind Dir.	Wind Speed (m/s)	Mix Ht. (m)	Rel. Humid. (%)	Air Temp. (K)	Air-Sea Temp (K)	Virt. Pot. Temp Grad. (K/m)	Sigma-Theta	Revised Air-Sea Temp (K)
9/19/85 9:00	30	9	259.7	1.3	500	78.8	289.45	-1.1	0.00	26.84	-1.10
9/19/85 10:00	30	9	235.4	1.3	500	79.0	289.95	-0.8	0.00	28.41	-0.80
9/19/85 11:00	30	9	214.1	2.6	500	80.1	290.15	-0.7	0.00	24.42	-0.70
9/19/85 12:00	30	9	252.9	3.1	500	80.1	290.25	-0.7	0.00	32.86	-0.70
9/22/85 9:00	30	9	220.8	1.0	500	70.6	290.55	0.5	0.02	32.13	0.50
9/22/85 10:00	30	9	251.1	1.2	500	81.0	290.15	0.3	0.02	17.43	0.30
9/22/85 11:00	30	9	253.8	2.4	500	92.1	289.55	1.0	0.02	7.97	1.00
9/22/85 11:00	30	9	230.0	2.4	500	92.1	289.55	1.0	0.02	7.97	1.00
9/22/85 12:00	30	9	248.4	2.8	500	91.1	289.45	1.1	0.02	17.43	1.10
9/22/85 12:00	30	9	237.7	2.8	500	91.1	289.45	1.1	0.02	17.43	1.10
9/25/85 10:00	24	9	163.8	1.0	500	60.3	294.35	2.8	0.01	41.67	2.80
9/25/85 11:00	46	9	163.8	1.6	500	69.9	294.15	2.3	0.01	9.87	2.30
9/25/85 12:00	46	9	165.6	1.0	500	90.3	294.05	2.1	0.01	26.06	2.10
9/25/85 13:00	46	9	175.0	1.0	500	90.4	294.55	2.7	0.01	18.37	2.70
9/26/85 12:00	49	9	262.0	3.8	500	83.5	291.85	-0.7	0.00	10.87	-0.70
9/26/85 13:00	49	9	262.2	4.0	500	81.0	291.95	-1.0	0.00	11.80	-1.00
9/28/85 10:00	24	9	155.8	5.4	500	85.1	291.25	-0.6	0.00	8.92	-0.60
9/28/85 10:00	24	9	155.8	5.4	500	85.1	291.25	-0.6	0.00	8.92	-0.60
9/28/85 11:00	24	9	174.7	3.2	500	84.1	291.15	-0.8	0.00	10.87	-0.80
9/28/85 11:00	24	9	177.0	3.2	500	84.1	291.15	-0.8	0.00	10.87	-0.80
9/28/85 13:00	24	9	234.5	1.5	500	82.5	291.45	-0.6	0.00	10.87	-0.60
9/28/85 13:00	24	9	229.5	1.5	500	82.5	291.45	-0.6	0.00	10.87	-0.60
9/28/85 14:00	24	9	215.0	2.1	500	81.7	291.65	-0.3	0.00	11.80	-0.30
9/28/85 14:00	24	9	215.0	2.1	500	81.7	291.65	-0.3	0.00	11.80	-0.30
9/29/85 11:00	30	9	243.7	3.4	500	86.0	291.35	-0.3	0.00	18.37	-0.30
9/29/85 12:00	30	9	238.9	3.1	500	87.8	291.25	-0.4	0.00	4.97	-0.40
9/29/85 12:00	30	9	232.7	3.1	500	87.8	291.25	-0.4	0.00	4.97	-0.40

Table 7 Carpinteria Source Parameters

Date/Time	Release Type [1]	Rel. Ht. (m)	UTM East (m)	UTM North (m)
9/19/85 9:00	SF6	30.5	270,343	3,806,910
9/19/85 10:00	SF6	30.5	270,343	3,806,910
9/19/85 11:00	SF6	30.5	270,343	3,806,910
9/19/85 12:00	SF6	30.5	270,343	3,806,910
9/22/85 9:00	SF6	18.3	270,133	3,806,520
9/22/85 10:00	SF6	18.3	270,133	3,806,520
9/22/85 11:00	SF6	18.3	270,133	3,806,520
9/22/85 11:00	Freon	36.6	270,133	3,806,520
9/22/85 12:00	SF6	18.3	270,133	3,806,520
9/22/85 12:00	Freon	36.6	270,133	3,806,520
9/25/85 10:00	SF6	24.4	271,024	3,806,660
9/25/85 11:00	SF6	24.4	271,024	3,806,660
9/25/85 12:00	SF6	24.4	271,024	3,806,660
9/25/85 13:00	SF6	24.4	271,024	3,806,660
9/26/85 12:00	Freon	24.4	269,524	3,807,330
9/26/85 13:00	Freon	24.4	269,524	3,807,330
9/28/85 10:00	SF6	24.4	271,289	3,806,340
9/28/85 10:00	Freon	42.7	271,289	3,806,340
9/28/85 11:00	SF6	24.4	271,289	3,806,340
9/28/85 11:00	Freon	42.7	271,289	3,806,340
9/28/85 13:00	SF6	24.4	270,133	3,806,520
9/28/85 13:00	Freon	39.6	270,133	3,806,520
9/28/85 14:00	SF6	24.4	270,133	3,806,520
9/28/85 14:00	Freon	39.6	270,133	3,806,520
9/29/85 11:00	SF6	30.5	270,133	3,806,520
9/29/85 12:00	SF6	30.5	270,133	3,806,520
9/29/85 12:00	Freon	61.0	270,133	3,806,520

1. For some hours releases were from two different heights using different tracer gases. Actual source and receptor locations were used in the simulations where receptor heights and scale heights were calculated with AERMAP. There was no building downwash assumed for these simulations.

Table 8 Performance Evaluation Statistical Results by Data Set and COARE-AERMOD Case

Data Set	Case	Description	Geom. Mean (µs/m3)	Geom. Std.	MG	VG	Geom. Correl. Coef.	Frac. Factor of 2	RHC (µs/m3)
All Data (84 samples)	0	Observations	5.9	1.30	1.00	1.00	1.00	1.00	128
	1	Abs(L)>5, Obs σΘ, Venk Zi	5.8	1.61	1.02	3.59	0.72	**0.49**	**130**
	2	Abs(L)>5, Pred σΘ, Venk Zi	8.2	1.72	0.72	4.89	0.71	0.45	286
	3	Abs(L)>1, Obs σΘ, Obs Zi	5.5	1.71	1.08	4.45	0.70	0.45	446
	4	Abs(L)>5, Obs σΘ, Obs Zi	5.8	1.59	1.03	3.36	0.73	0.45	310
	5	Abs(L)>5, Obs σΘ, Venk Zi, Draxler σy	**5.9**	**1.52**	**1.01**	**2.93**	**0.74**	0.48	111
Pismo Beach, CA (31 samples)	0	Observations	3.5	0.50	1.00	1.00	1.00	1.00	9
	1	Abs(L)>5, Obs σΘ, Venk Zi	3.7	1.40	0.93	6.20	0.28	**0.48**	43
	2	Abs(L)>5, Pred σΘ, Venk Zi	5.8	1.46	0.59	13.10	0.05	0.29	55
	3	Abs(L)>1, Obs σΘ, Obs Zi	3.2	1.41	1.09	7.70	0.15	0.45	**19**
	4	Abs(L)>5, Obs σΘ, Obs Zi	3.8	**1.23**	0.91	**4.27**	0.27	**0.48**	20
	5	Abs(L)>5, Obs σΘ, Venk Zi, Draxler σy	**3.4**	1.33	**1.04**	4.75	**0.35**	0.42	30
Cameron, LA (26 samples)	0	Observations	3.2	1.41	1.00	1.00	1.00	1.00	41
	1	Abs(L)>5, Obs σΘ, Venk Zi	4.0	1.84	0.79	2.99	0.84	0.42	49
	2	Abs(L)>5, Pred σΘ, Venk Zi	4.1	1.87	0.77	3.55	0.81	0.42	53
	3	Abs(L)>1, Obs σΘ, Obs Zi	**3.7**	1.77	**0.86**	2.64	0.84	**0.46**	**40**
	4	Abs(L)>5, Obs σΘ, Obs Zi	3.7	1.79	0.85	2.65	**0.84**	**0.46**	44
	5	Abs(L)>5, Obs σΘ, Venk Zi, Draxler σy	4.1	**1.70**	0.76	**2.58**	0.84	**0.46**	36
Carpinteria, CA (27 samples)	0	Observations	20.1	0.93	1.00	1.00	1.00	1.00	137
	1	Abs(L)>5, Obs σΘ, Venk Zi	13.9	1.18	1.45	2.29	0.71	0.56	172
	2	Abs(L)>5, Pred σΘ, Venk Zi	**24.3**	1.30	**0.83**	2.15	**0.76**	**0.67**	330
	3	Abs(L)>1, Obs σΘ, Obs Zi	15.0	1.50	1.34	3.93	0.66	0.44	470
	4	Abs(L)>5, Obs σΘ, Obs Zi	14.2	1.37	1.42	3.21	0.67	0.41	329
	5	Abs(L)>5, Obs σΘ, Venk Zi, Draxler σy	15.5	**0.97**	1.30	**1.90**	0.69	0.56	**129**

VG is a measure of geometric variance or scatter, VG = exp(average(ln(Co/Cp)))
MG is a measure of bias about the geometric mean, MG = exp(average((ln(Co/Cp))^2))
RHC = "Robust Highest Concentration" based on top 11 samples
Best performing modeling approach or Case is highlighted in **red**

Figure 1: Beaufort Sea Lease Block Locations

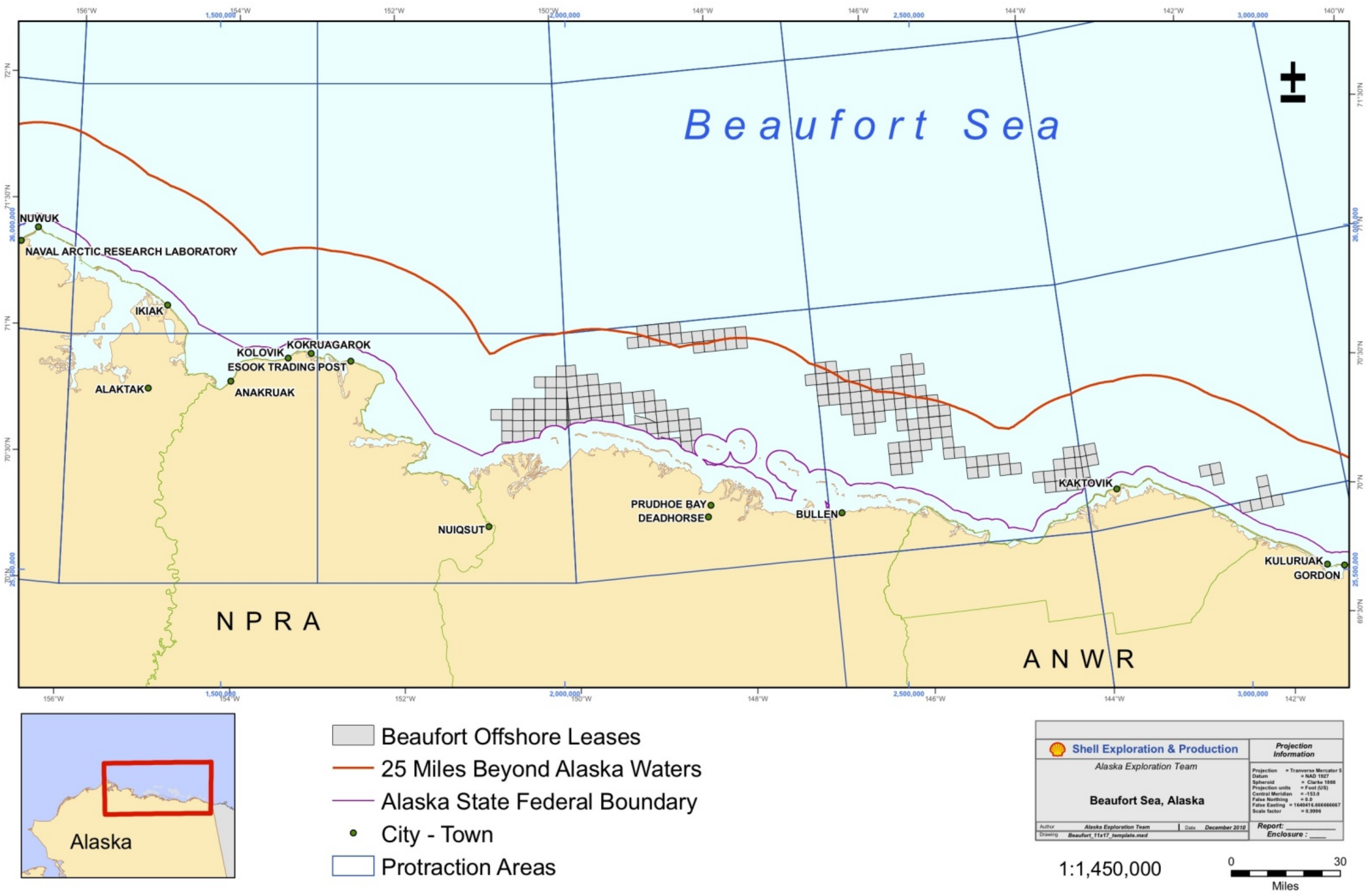


Figure 2: Map of Shell Meteorological Monitoring Stations in the Beaufort and Chukchi Sea Region

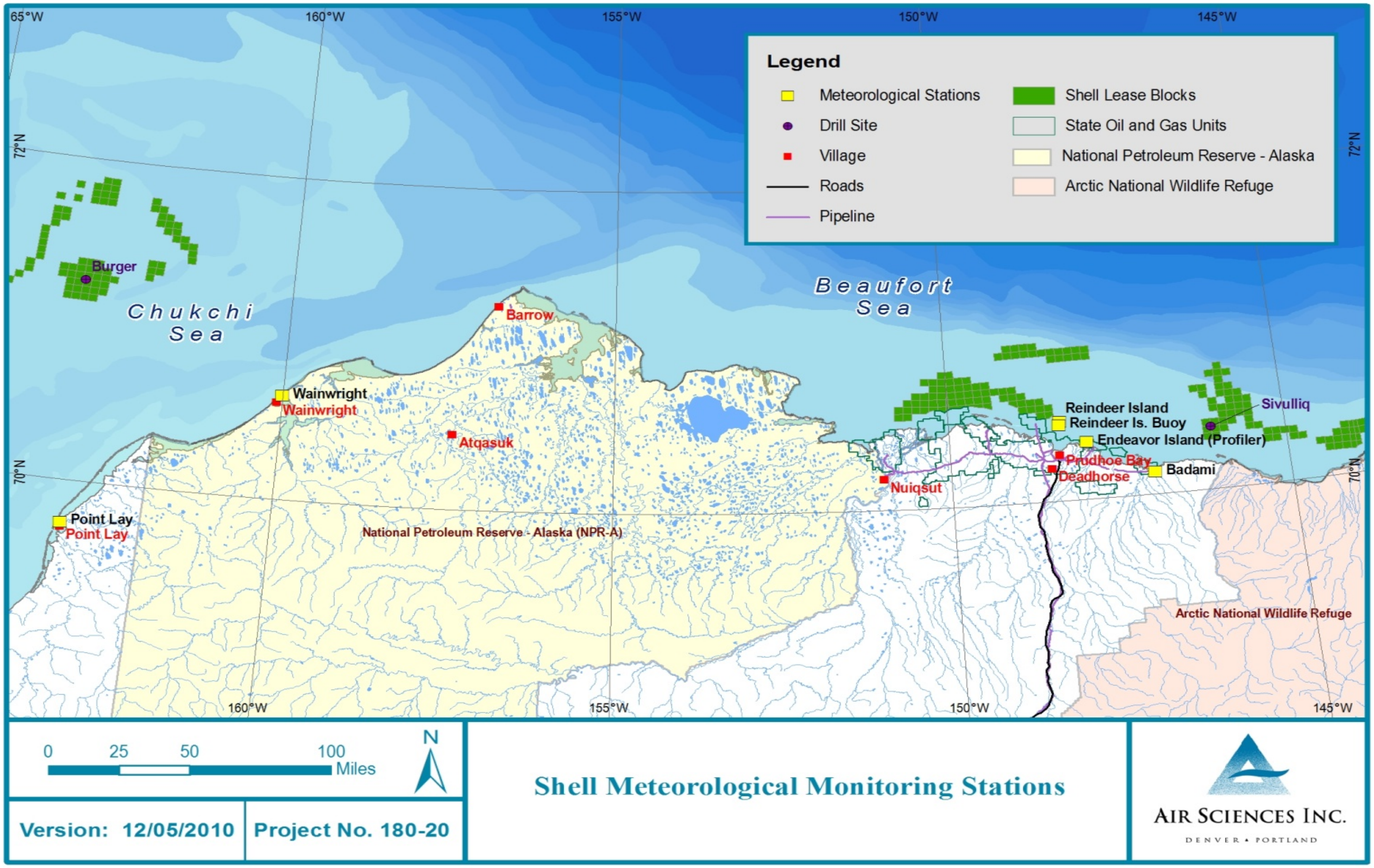


Figure 3.

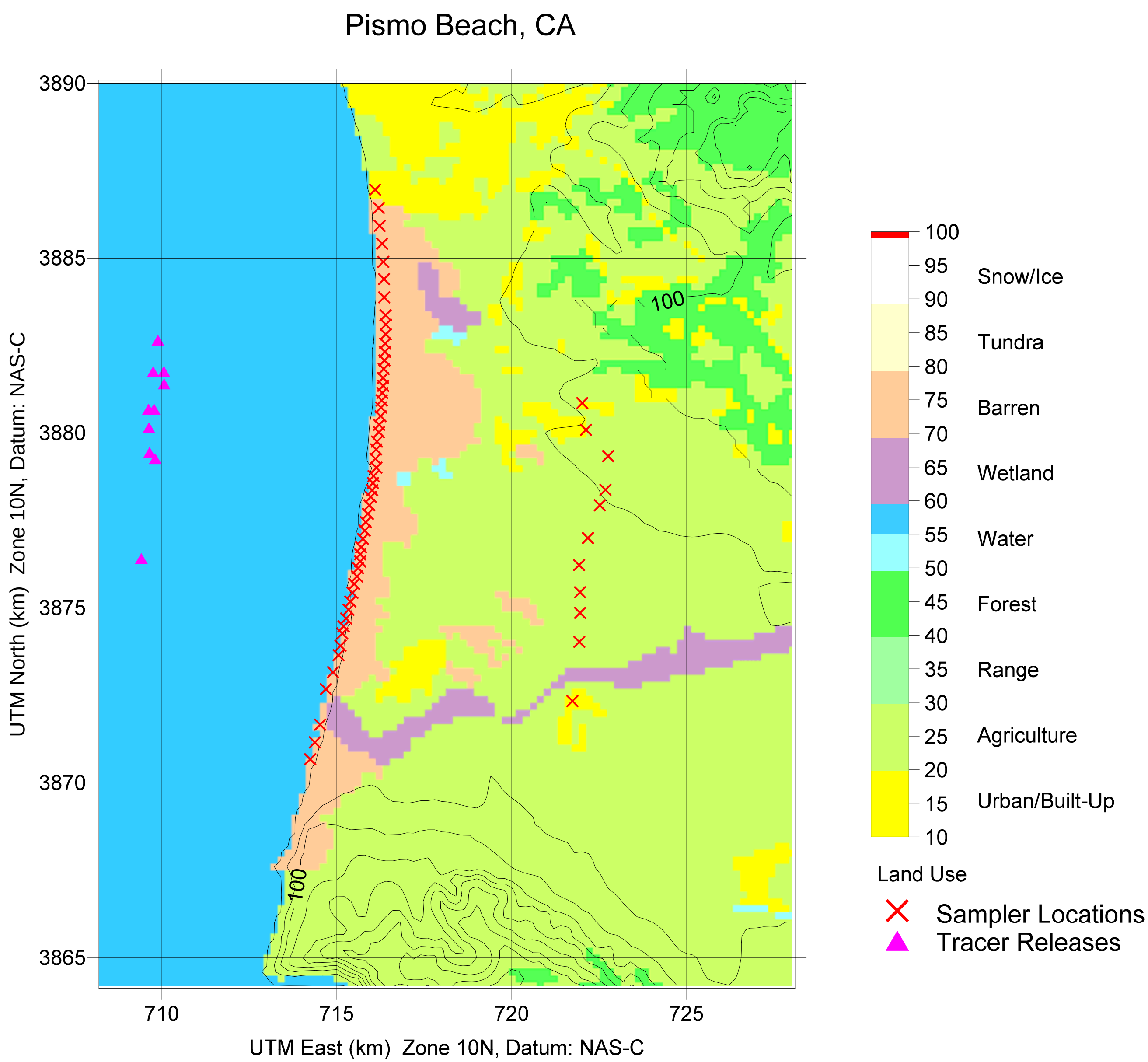

Pismo Beach, CA
3890
3885
3880
3875
3870
3865
710
715
720
725
UTM East (km) Zone 10N, Datum: NAS-C
UTM North (km) Zone 10N, Datum: NAS-C
100
100
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
Snow/Ice
Tundra
Barren
Wetland
Water
Forest
Range
Agriculture
Urban/Built-Up
Land Use
Sampler Locations
Tracer Releases

Figure 4

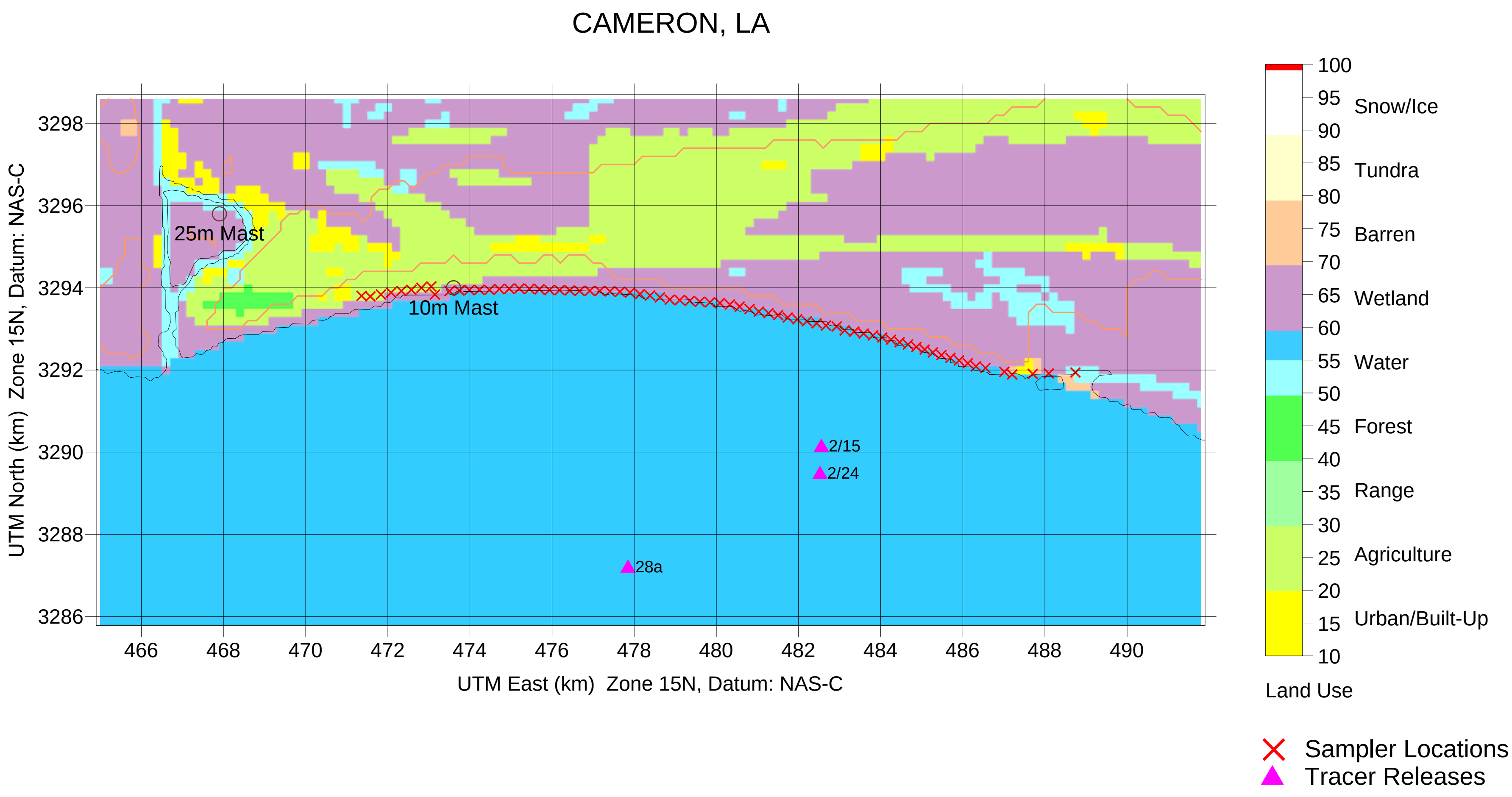

CAMERON, LA
25m Mast
10m Mast
2/15
2/24
28a
UTM North (km) Zone 15N, Datum: NAS-C
UTM East (km) Zone 15N, Datum: NAS-C
3286
3288
3290
3292
3294
3296
3298
466
468
470
472
474
476
478
480
482
484
486
488
490
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
Snow/Ice
Tundra
Barren
Wetland
Water
Forest
Range
Agriculture
Urban/Built-Up
Land Use
Sampler Locations
Tracer Releases

Figure 5

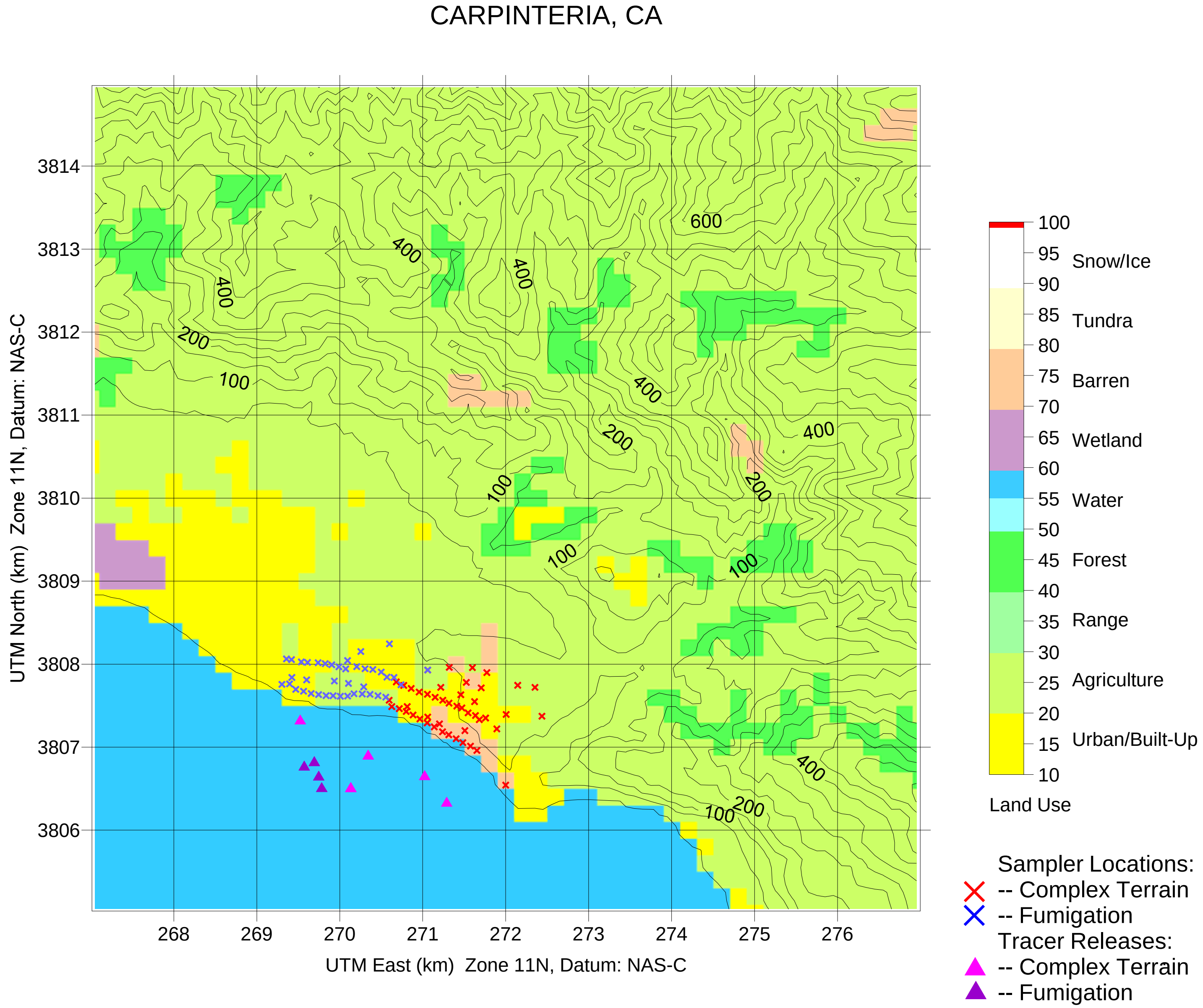

CARPINTERIA, CA
UTM North (km) Zone 11N, Datum: NAS-C
UTM East (km) Zone 11N, Datum: NAS-C
3806
3807
3808
3809
3810
3811
3812
3813
3814
268
269
270
271
272
273
274
275
276
100
200
400
600
Snow/Ice
Tundra
Barren
Wetland
Water
Forest
Range
Agriculture
Urban/Built-Up
Land Use
Sampler Locations:
-- Complex Terrain
-- Fumigation
Tracer Releases:
-- Complex Terrain
-- Fumigation

Figure 6

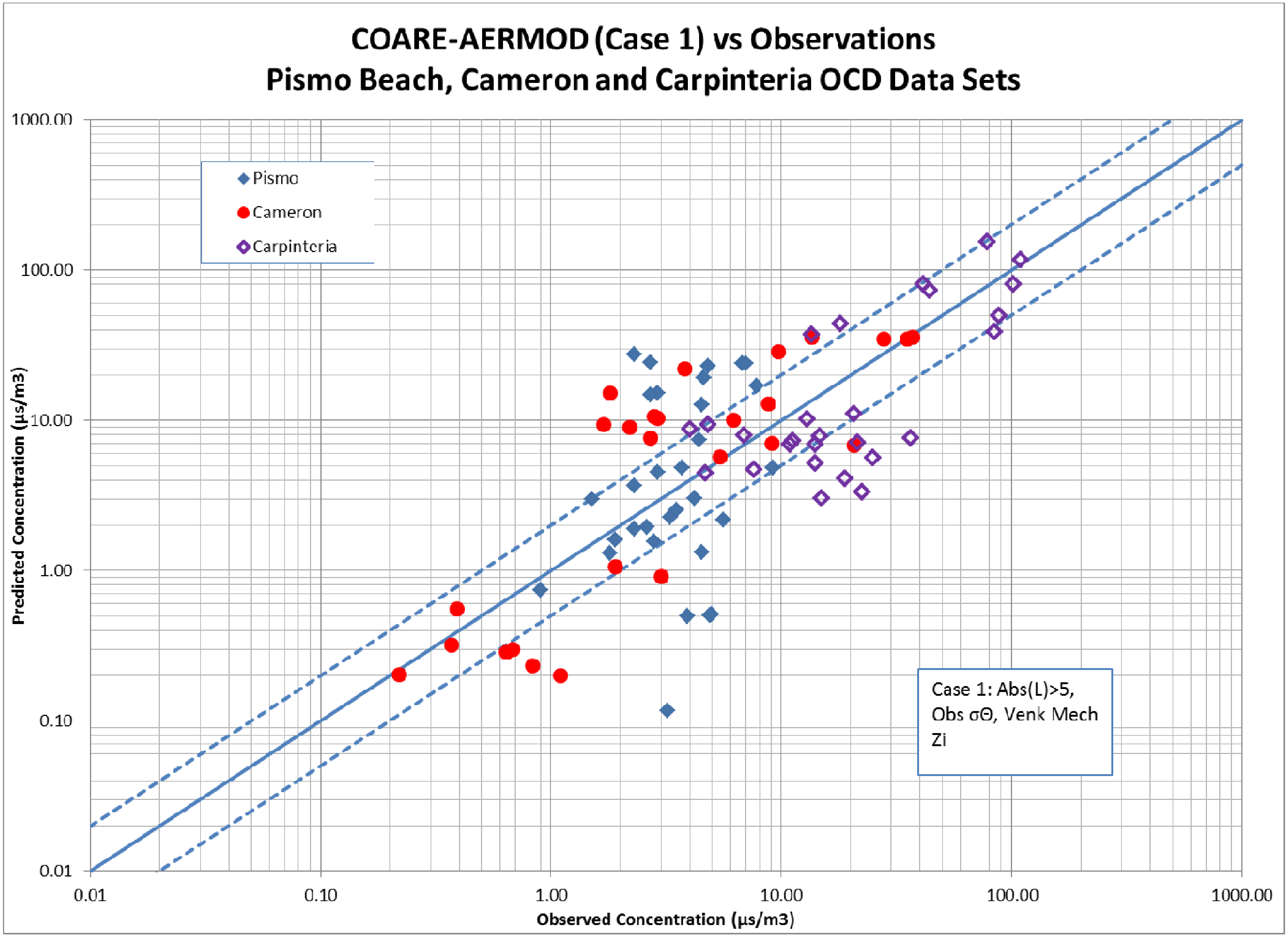
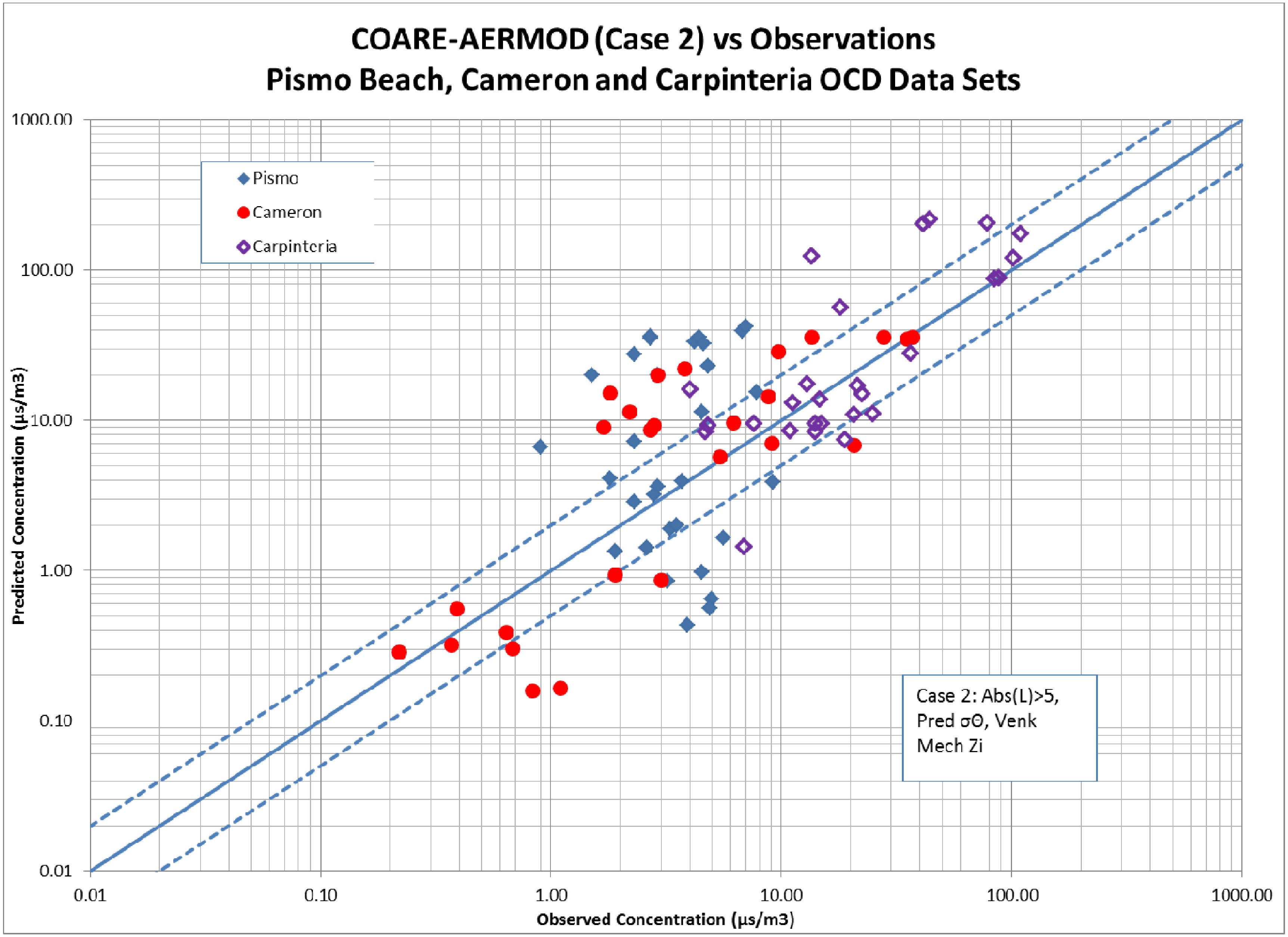

COARE-AERMOD (Case 1) vs Observations
Pismo Beach, Cameron and Carpinteria OCD Data Sets
Pismo
Cameron
Carpinteria
Case 1: Abs(L)>5, Obs σΘ, Venk Mech Zi
Predicted Concentration (µs/m3)
Observed Concentration (µs/m3)
1000.00
100.00
10.00
1.00
0.10
0.01
0.01
0.10
1.00
10.00
100.00
1000.00

Figure 7



COARE-AERMOD (Case 2) vs Observations
Pismo Beach, Cameron and Carpintería OCD Data Sets
Pismo
Cameron
Carpinteria
Case 2: Abs(L)>5,
Pred σΘ, Venk
Mech Zi
Predicted Concentration (µs/m3)
Observed Concentration (µs/m3)
1000.00
100.00
10.00
1.00
0.10
0.01
0.01
0.10
1.00
10.00
100.00
1000.00

Figure 8

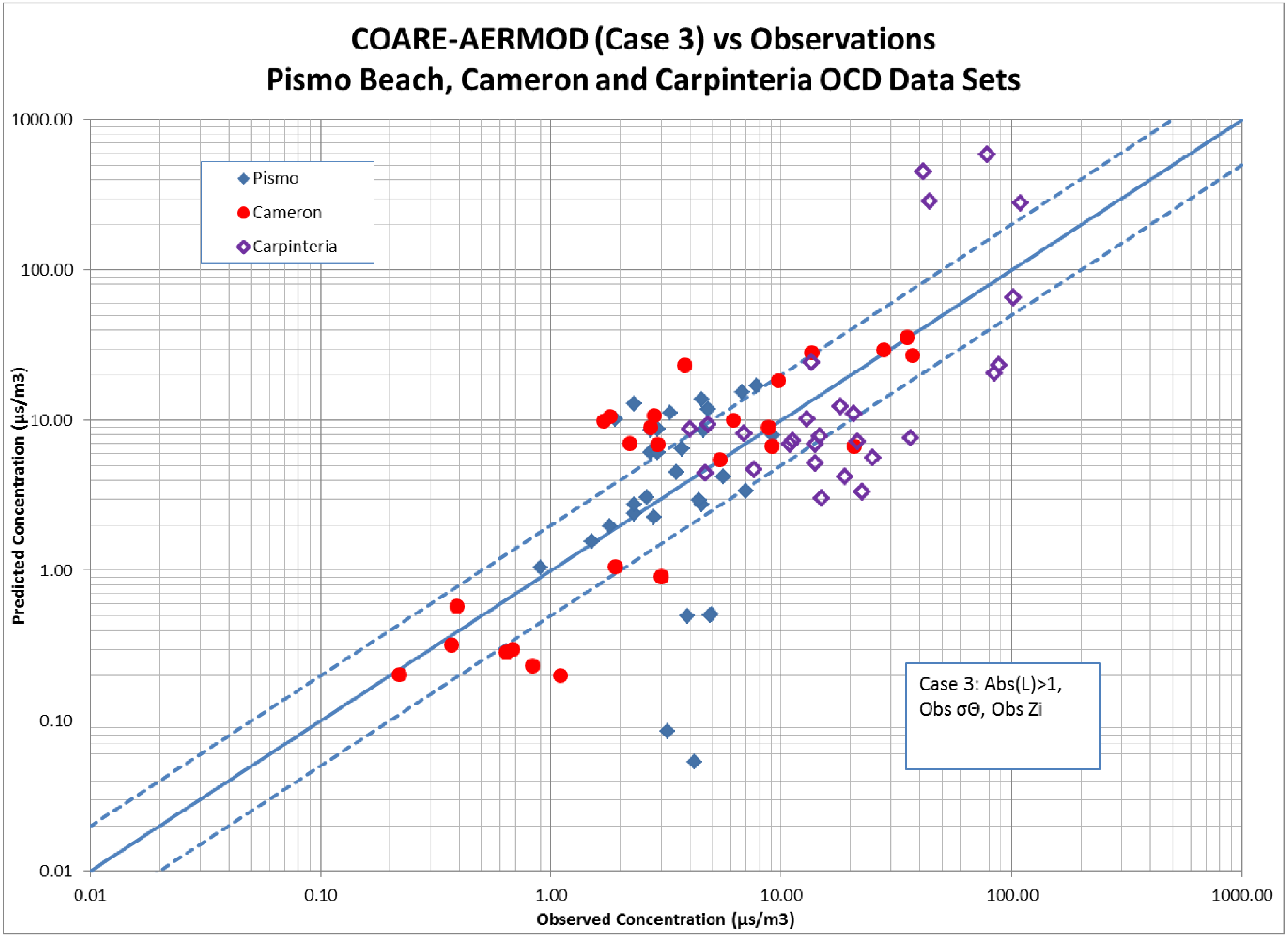
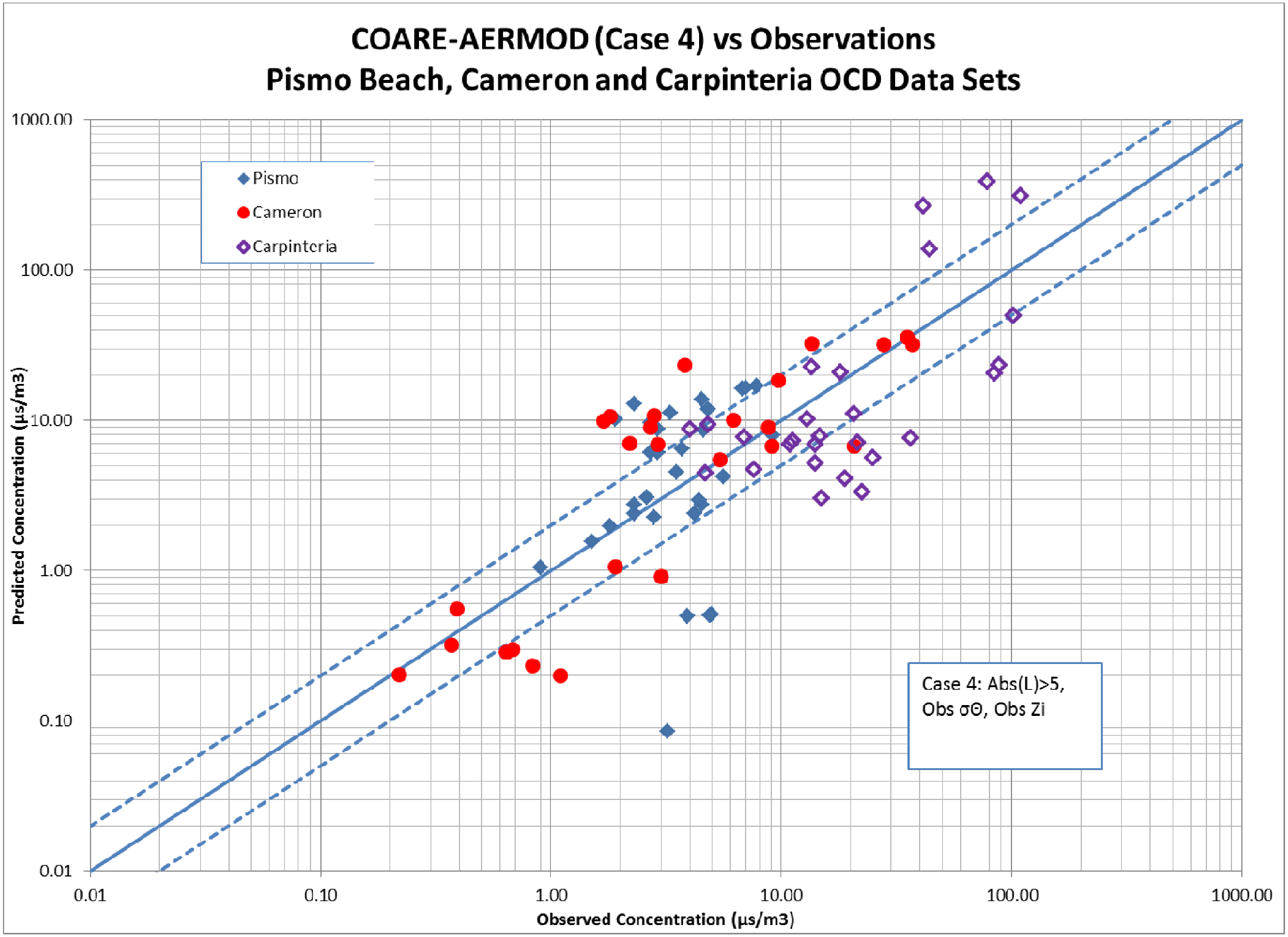
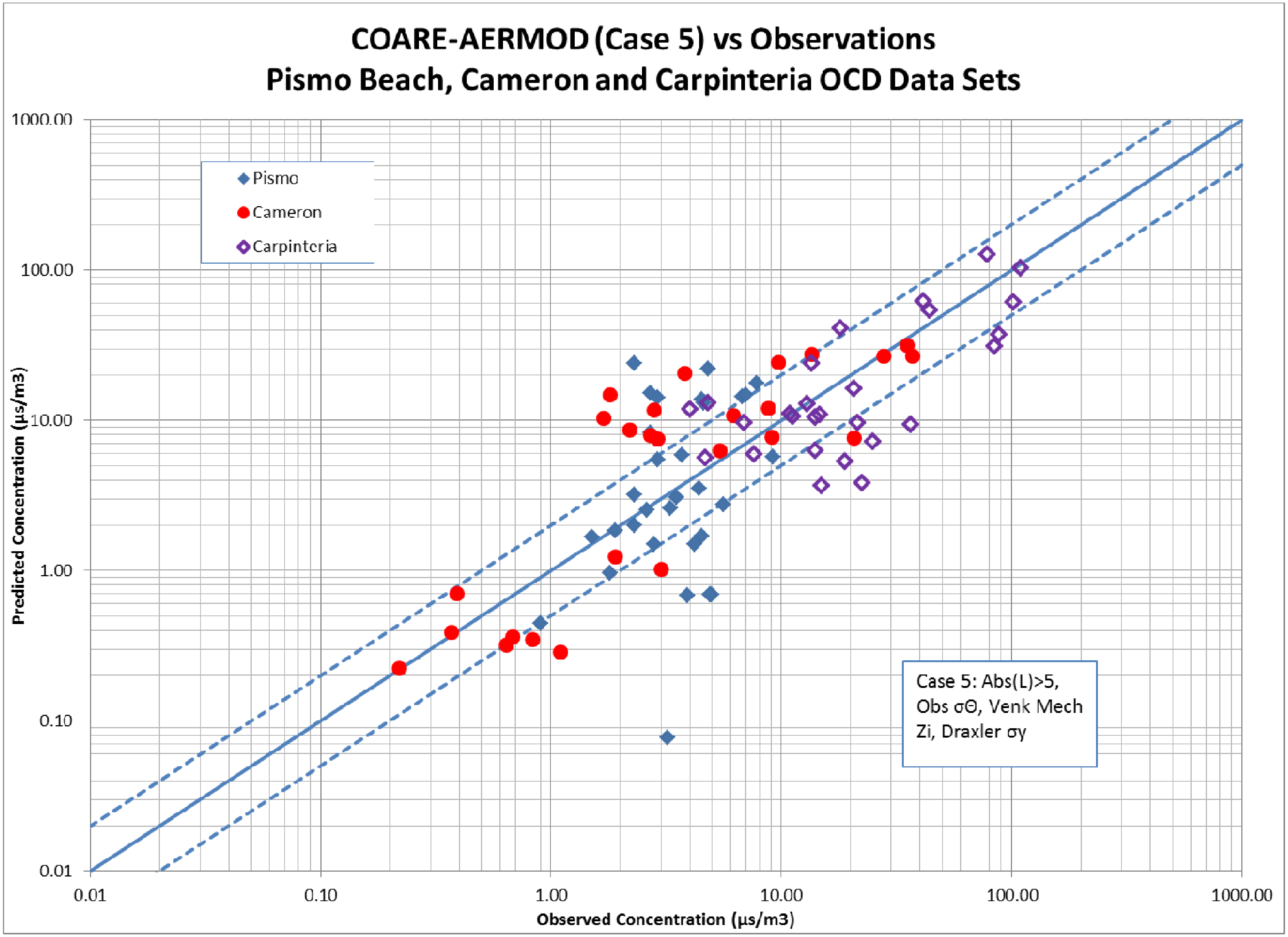

COARE-AERMOD (Case 3) vs Observations
Pismo Beach, Cameron and Carpinteria OCD Data Sets
Pismo
Cameron
Carpinteria
Case 3: Abs(L)>1,
Obs σΘ, Obs Zi
Predicted Concentration (µs/m3)
Observed Concentration (µs/m3)
1000.00
100.00
10.00
1.00
0.10
0.01
0.01
0.10
1.00
10.00
100.00
1000.00

Figure 9



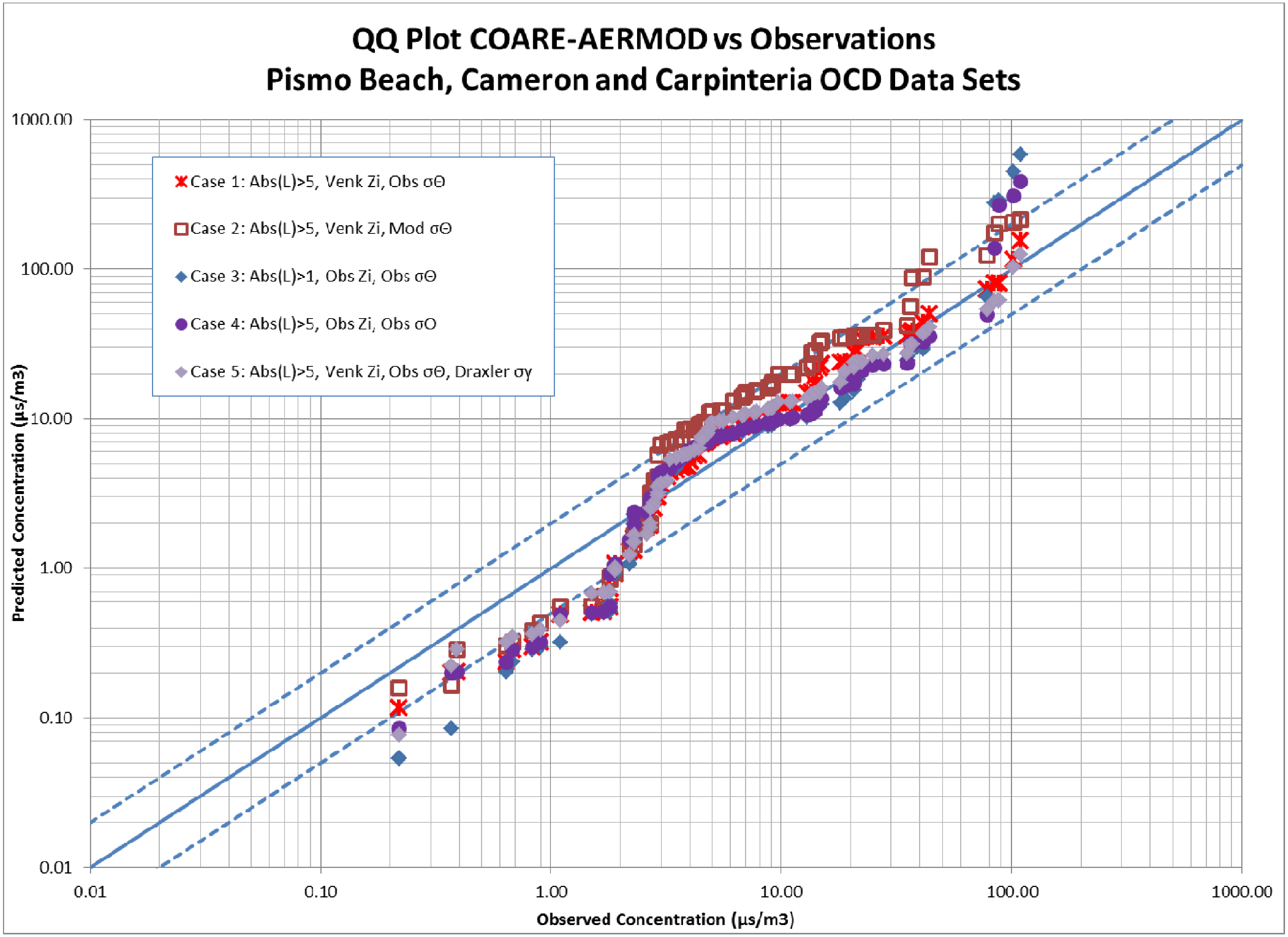
COARE-AERMOD (Case 4) vs Observations
Pismo Beach, Cameron and Carpinteria OCD Data Sets
Pismo
Cameron
Carpinteria
Case 4: Abs(L)>5,
Obs σΘ, Obs Zi
Predicted Concentration (µs/m3)
Observed Concentration (µs/m3)
1000.00
100.00
10.00
1.00
0.10
0.01
0.01
0.10
1.00
10.00
100.00
1000.00

Figure 10



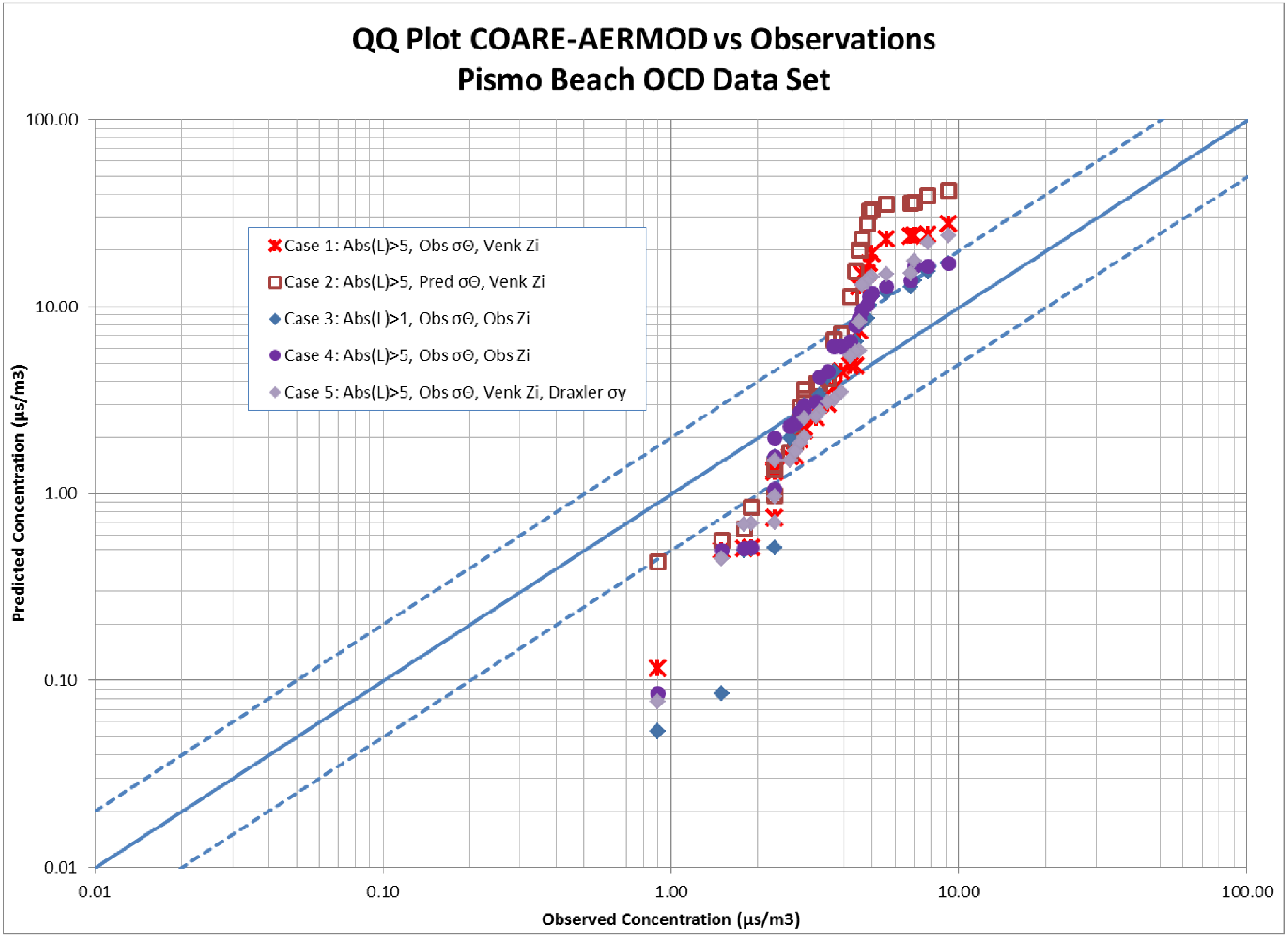
COARE-AERMOD (Case 5) vs Observations
Pismo Beach, Cameron and Carpinteria OCD Data Sets
Pismo
Cameron
Carpinteria
Case 5: Abs(L)>5,
Obs σΘ, Venk Mech
Zi, Draxler σy
Predicted Concentration (µs/m3)
Observed Concentration (µs/m3)
1000.00
100.00
10.00
1.00
0.10
0.01
0.01
0.10
1.00
10.00
100.00
1000.00

Figure 11



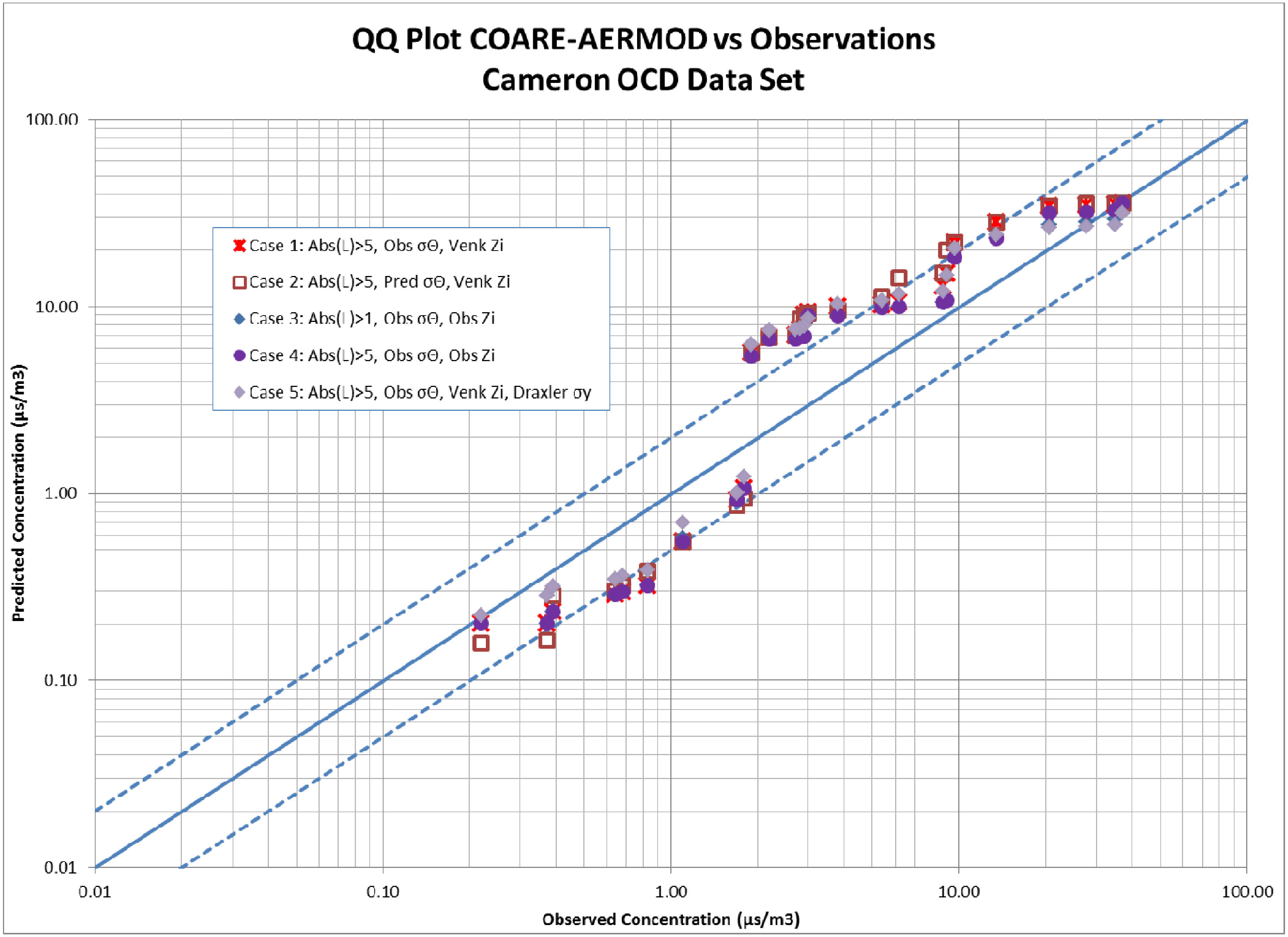
QQ Plot COARE-AERMOD vs Observations
Pismo Beach, Cameron and Carpinteria OCD Data Sets
Case 1: Abs(L)>5, Venk Zi, Obs σΘ
Case 2: Abs(L)>5, Venk Zi, Mod σΘ
Case 3: Abs(L)>1, Obs Zi, Obs σΘ
Case 4: Abs(L)>5, Obs Zi, Obs σO
Case 5: Abs(L)>5, Venk Zi, Obs σΘ, Draxler σy
Predicted Concentration (µs/m3)
Observed Concentration (µs/m3)
1000.00
100.00
10.00
1.00
0.10
0.01
0.01
0.10
1.00
10.00
100.00
1000.00

Figure 12



QQ Plot COARE-AERMOD vs Observations
Pismo Beach OCD Data Set
Case 1: Abs(L)>5, Obs σΘ, Venk Zi
Case 2: Abs(L)>5, Pred σΘ, Venk Zi
Case 3: Abs(L)>1, Obs σΘ, Obs Zi
Case 4: Abs(L)>5, Obs σΘ, Obs Zi
Case 5: Abs(L)>5, Obs σΘ, Venk Zi, Draxler σy
Predicted Concentration (µs/m3)
Observed Concentration (µs/m3)
100.00
10.00
1.00
0.10
0.01
0.01
0.10
1.00
10.00
100.00

Figure 13



QQ Plot COARE-AERMOD vs Observations
Cameron OCD Data Set
Case 1: Abs(L)>5, Obs σΘ, Venk Zi
Case 2: Abs(L)>5, Pred σΘ, Venk Zi
Case 3: Abs(L)>1, Obs σΘ, Obs Zi
Case 4: Abs(L)>5, Obs σΘ, Obs Zi
Case 5: Abs(L)>5, Obs σΘ, Venk Zi, Draxler σy
Predicted Concentration (µs/m3)
Observed Concentration (µs/m3)
100.00
10.00
1.00
0.10
0.01
0.01
0.10
1.00
10.00
100.00

Figure 14

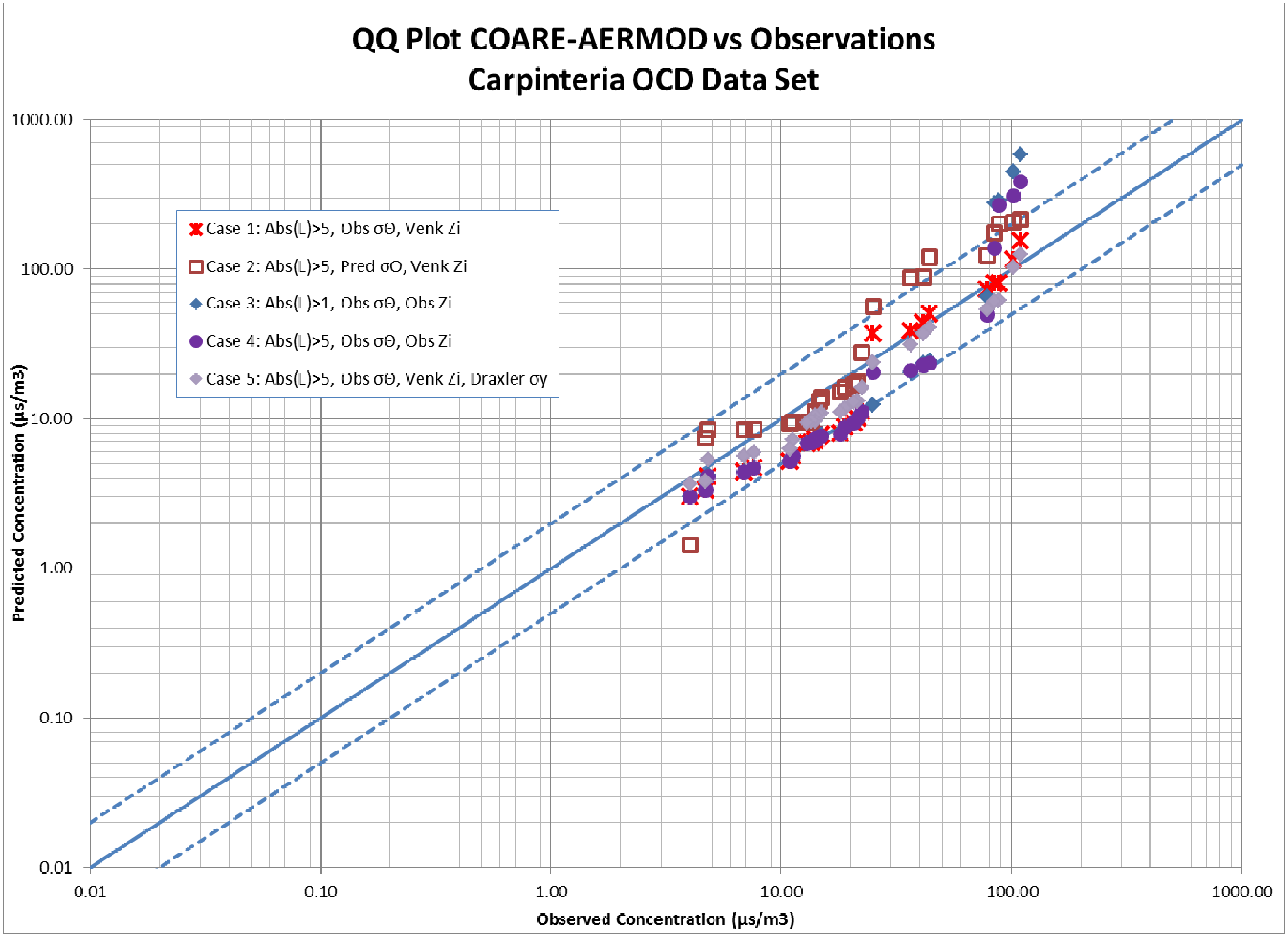
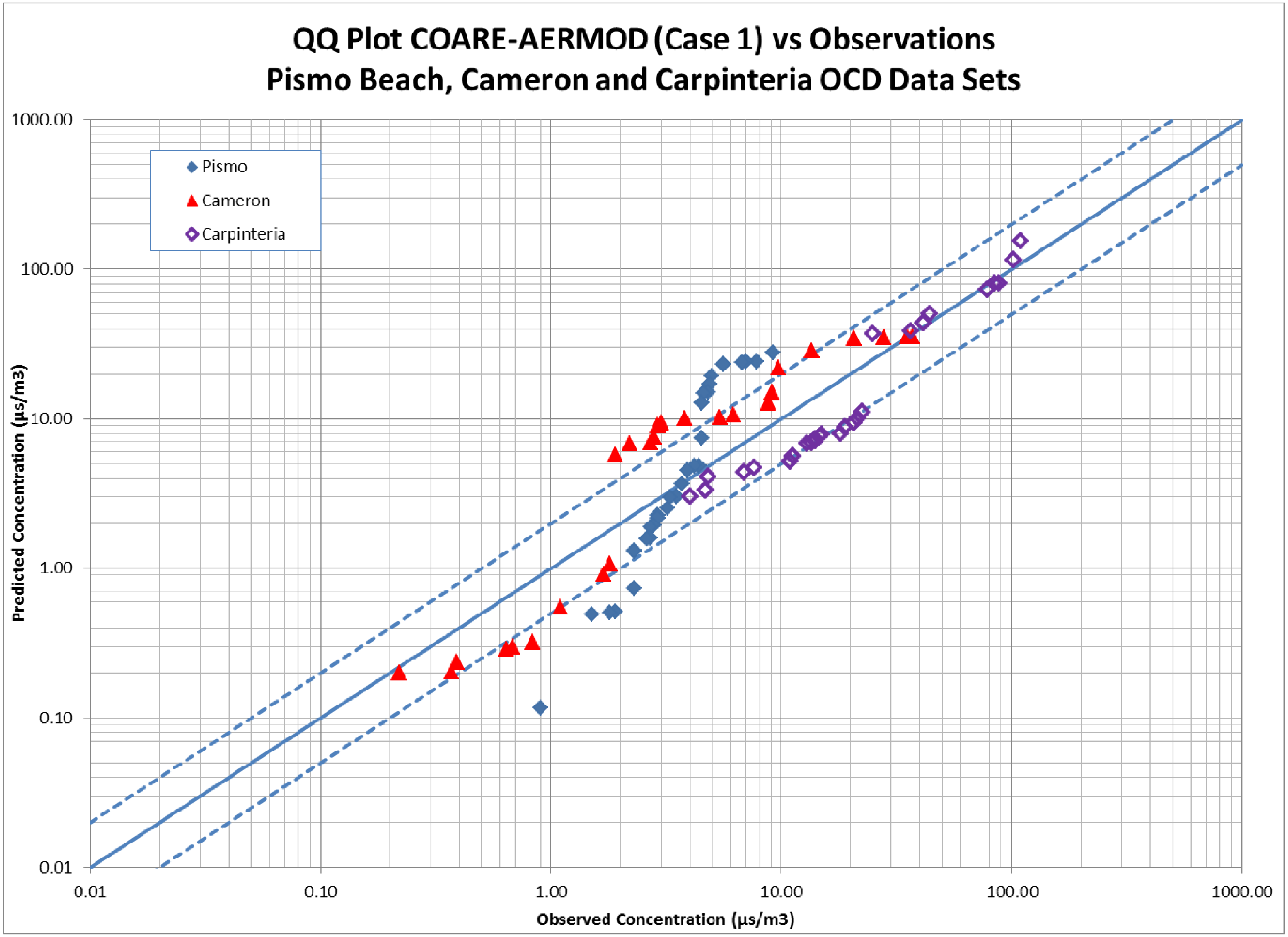
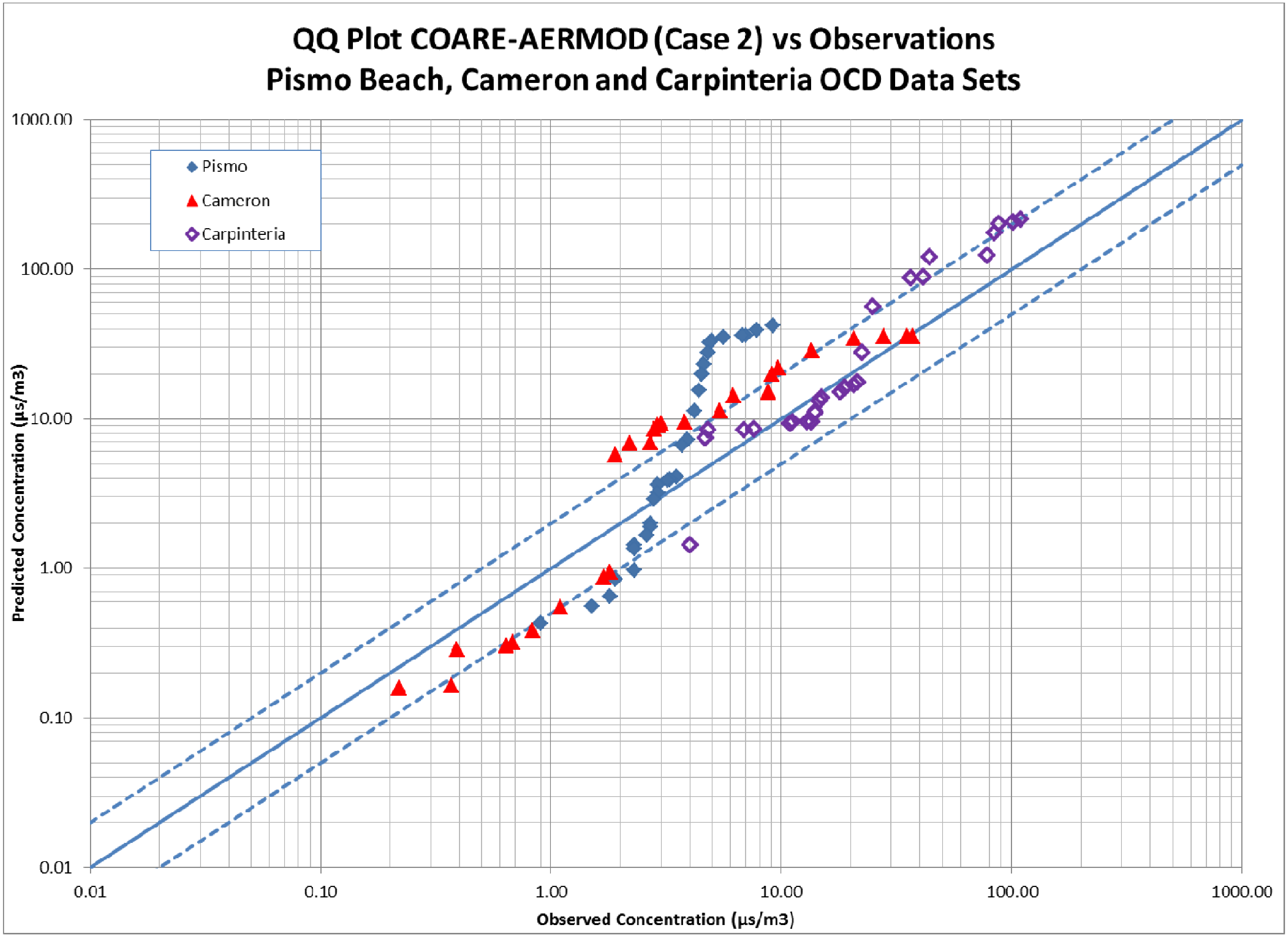

QQ Plot COARE-AERMOD vs Observations
Carpinteria OCD Data Set
Case 1: Abs(L)>5, Obs σΘ, Venk Zi
Case 2: Abs(L)>5, Pred σΘ, Venk Zi
Case 3: Abs(L)>1, Obs σΘ, Obs Zi
Case 4: Abs(L)>5, Obs σΘ, Obs Zi
Case 5: Abs(L)>5, Obs σΘ, Venk Zi, Draxler σy
Predicted Concentration (µs/m3)
1000.00
100.00
10.00
1.00
0.10
0.01
0.01
0.10
1.00
10.00
100.00
1000.00
Observed Concentration (µs/m3)

Figure 15



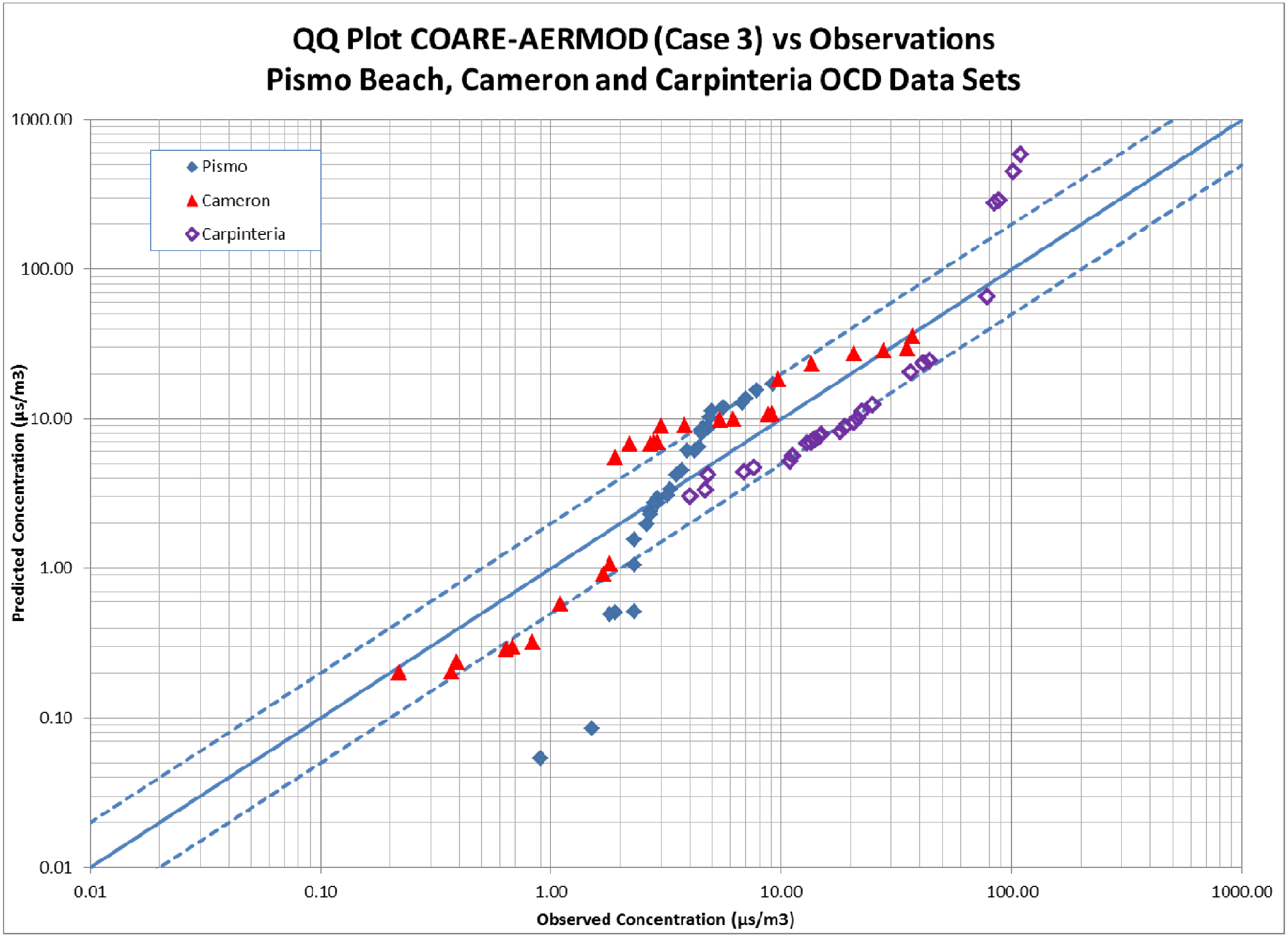
QQ Plot COARE-AERMOD (Case 1) vs Observations
Pismo Beach, Cameron and Carpinteria OCD Data Sets
Pismo
Cameron
Carpinteria
1000.00
100.00
10.00
1.00
0.10
0.01
Predicted Concentration (µs/m3)
0.01
0.10
1.00
10.00
100.00
1000.00
Observed Concentration (µs/m3)

Figure 16



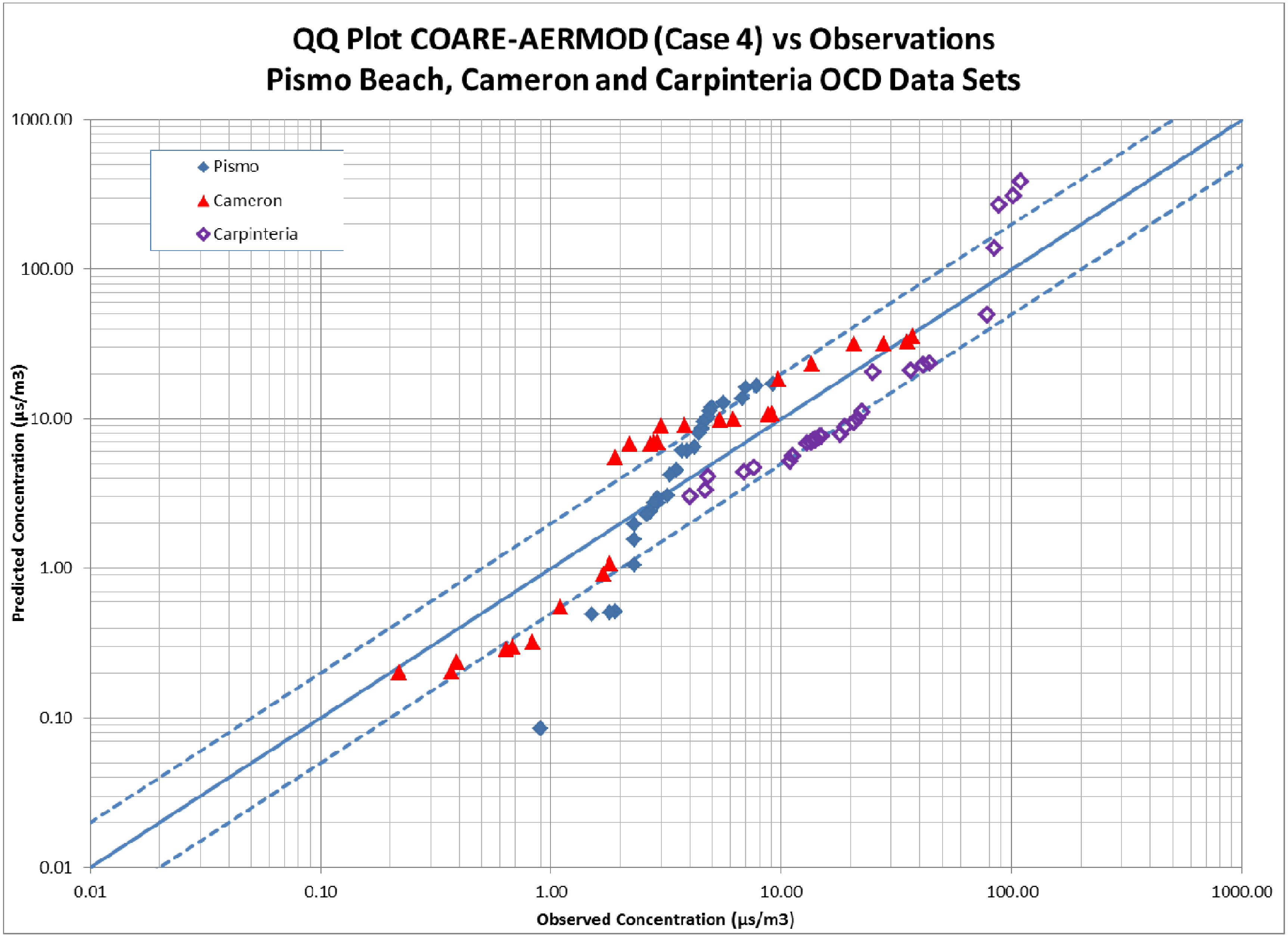
QQ Plot COARE-AERMOD (Case 2) vs Observations
Pismo Beach, Cameron and Carpinteria OCD Data Sets
Pismo
Cameron
Carpinteria
Predicted Concentration (µs/m3)
Observed Concentration (µs/m3)
1000.00
100.00
10.00
1.00
0.10
0.01
0.01
0.10
1.00
10.00
100.00
1000.00

Figure 17



QQ Plot COARE-AERMOD (Case 3) vs Observations
Pismo Beach, Cameron and Carpinteria OCD Data Sets
Pismo
Cameron
Carpinteria
Predicted Concentration (µs/m3)
Observed Concentration (µs/m3)
1000.00
100.00
10.00
1.00
0.10
0.01
0.01
0.10
1.00
10.00
100.00
1000.00

Figure 18



QQ Plot COARE-AERMOD (Case 4) vs Observations
Pismo Beach, Cameron and Carpinteria OCD Data Sets
Pismo
Cameron
Carpinteria
Predicted Concentration (µs/m3)
Observed Concentration (µs/m3)
1000.00
100.00
10.00
1.00
0.10
0.01
0.01
0.10
1.00
10.00
100.00
1000.00

Figure 19

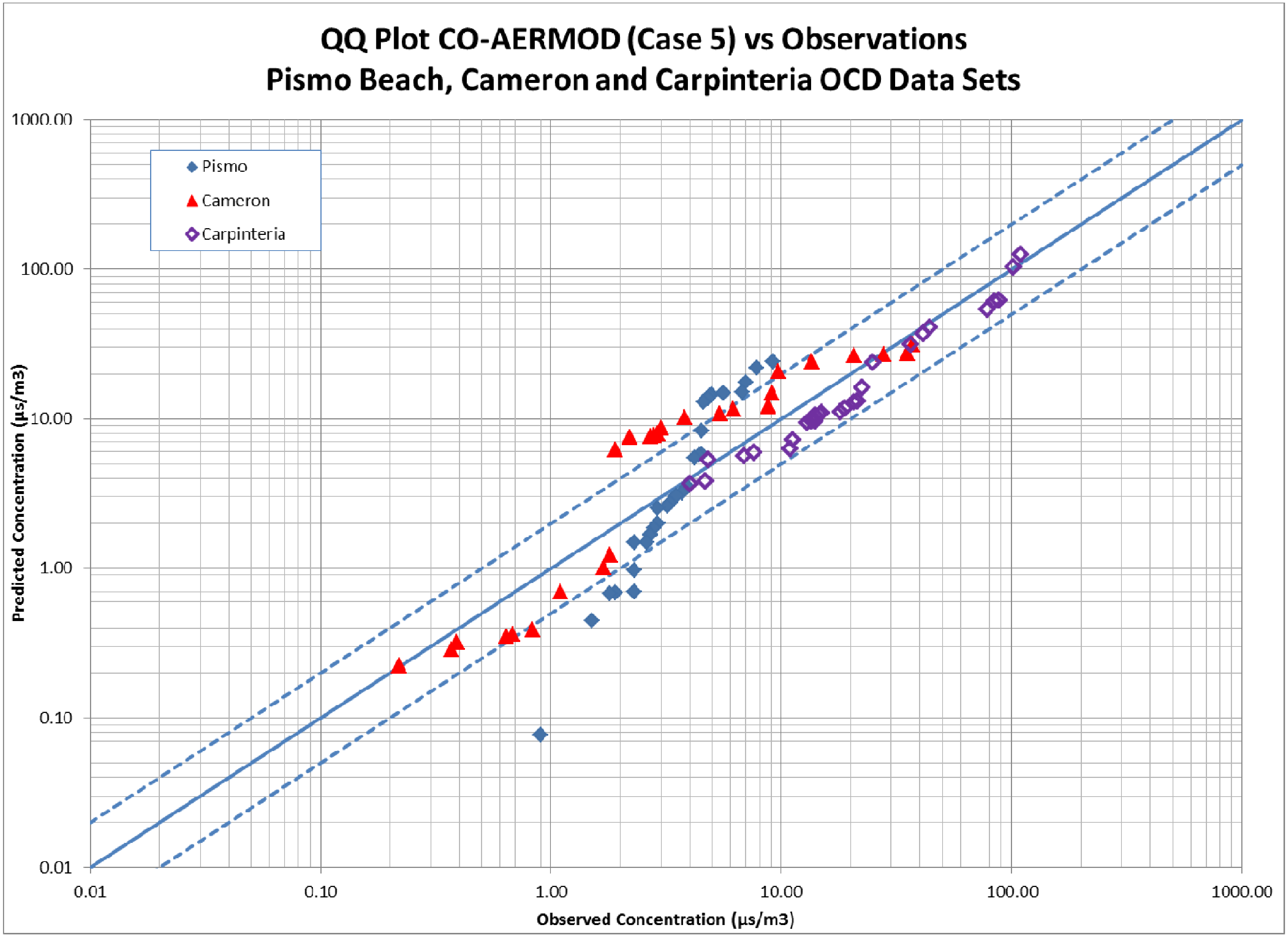
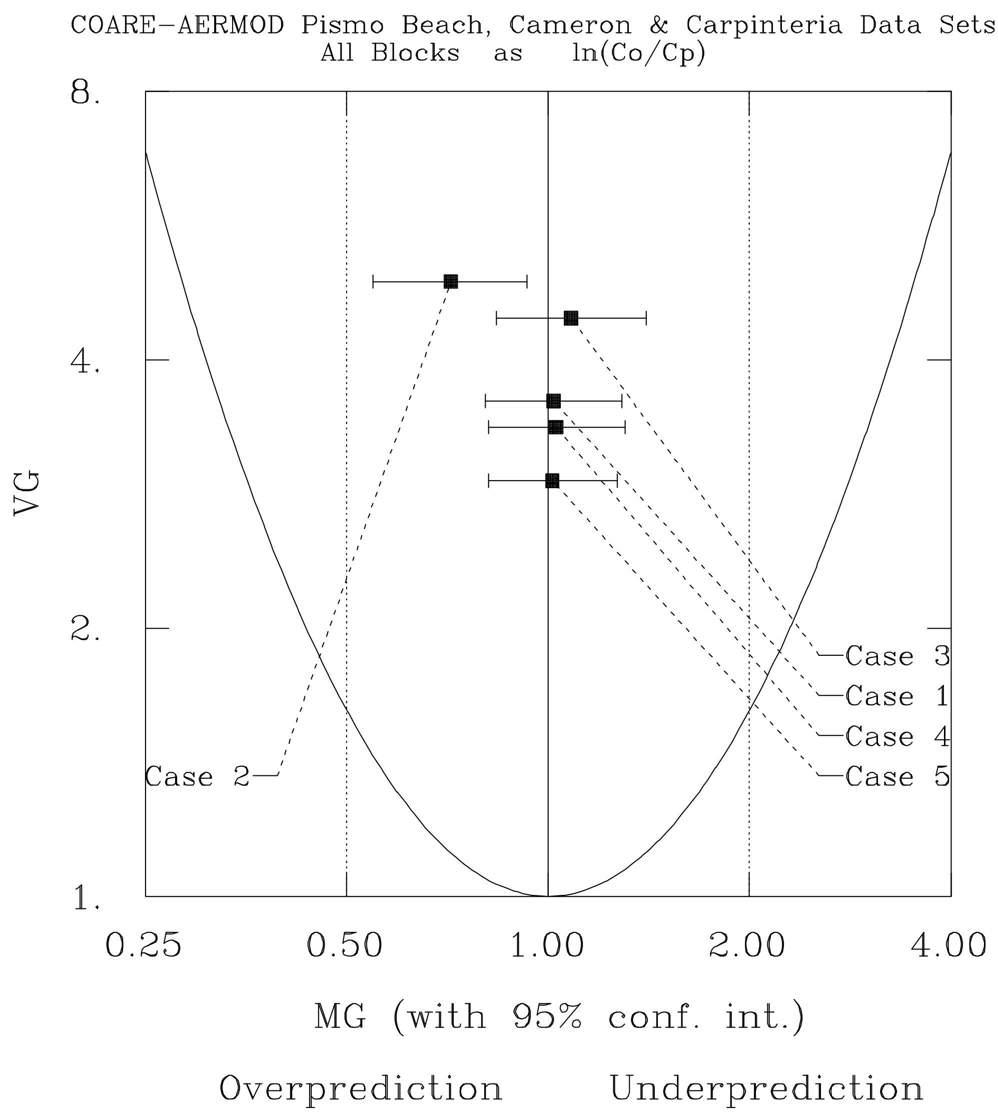
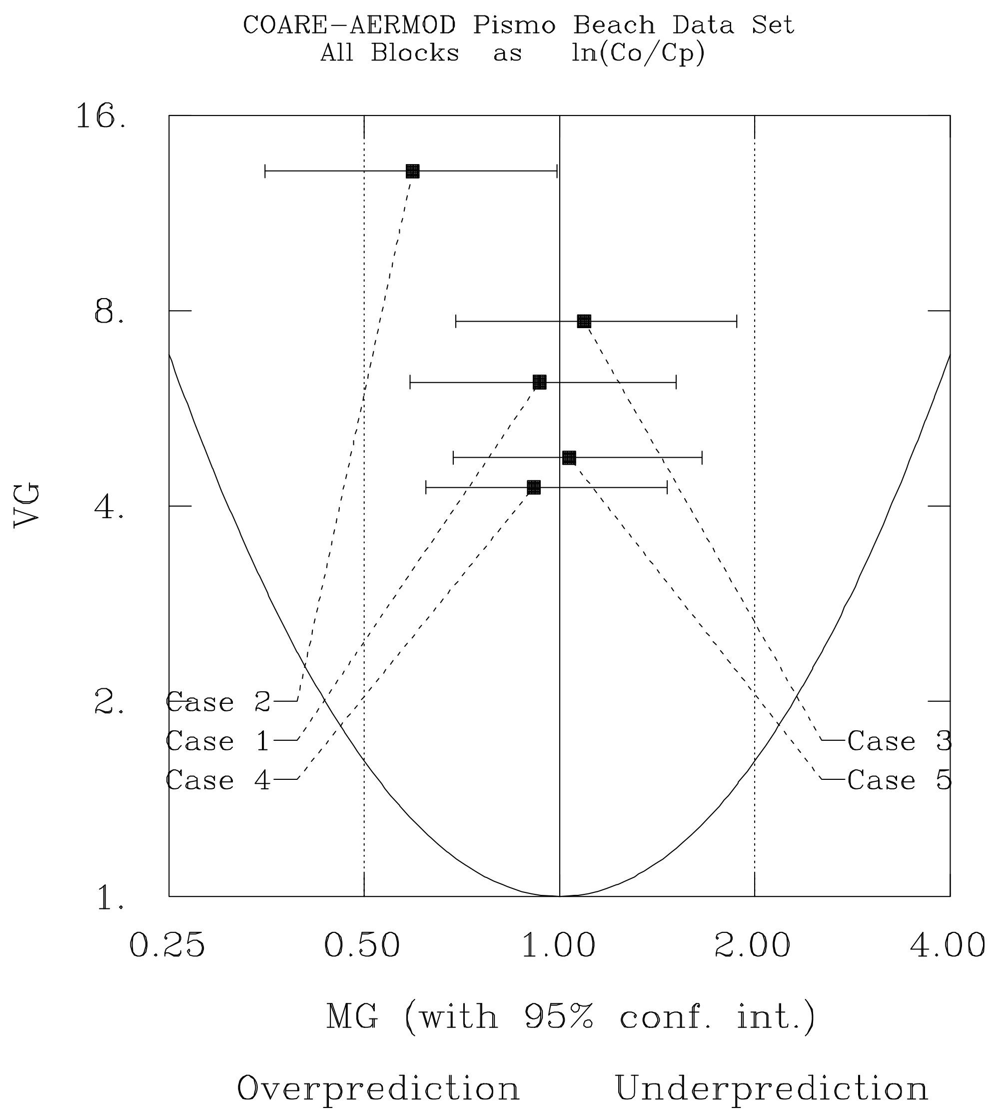

QQ Plot CO-AERMOD (Case 5) vs Observations
Pismo Beach, Cameron and Carpinteria OCD Data Sets
Pismo
Cameron
Carpinteria
Predicted Concentration (µs/m3)
Observed Concentration (µs/m3)
1000.00
100.00
10.00
1.00
0.10
0.01
0.01
0.10
1.00
10.00
100.00
1000.00

Figure 20



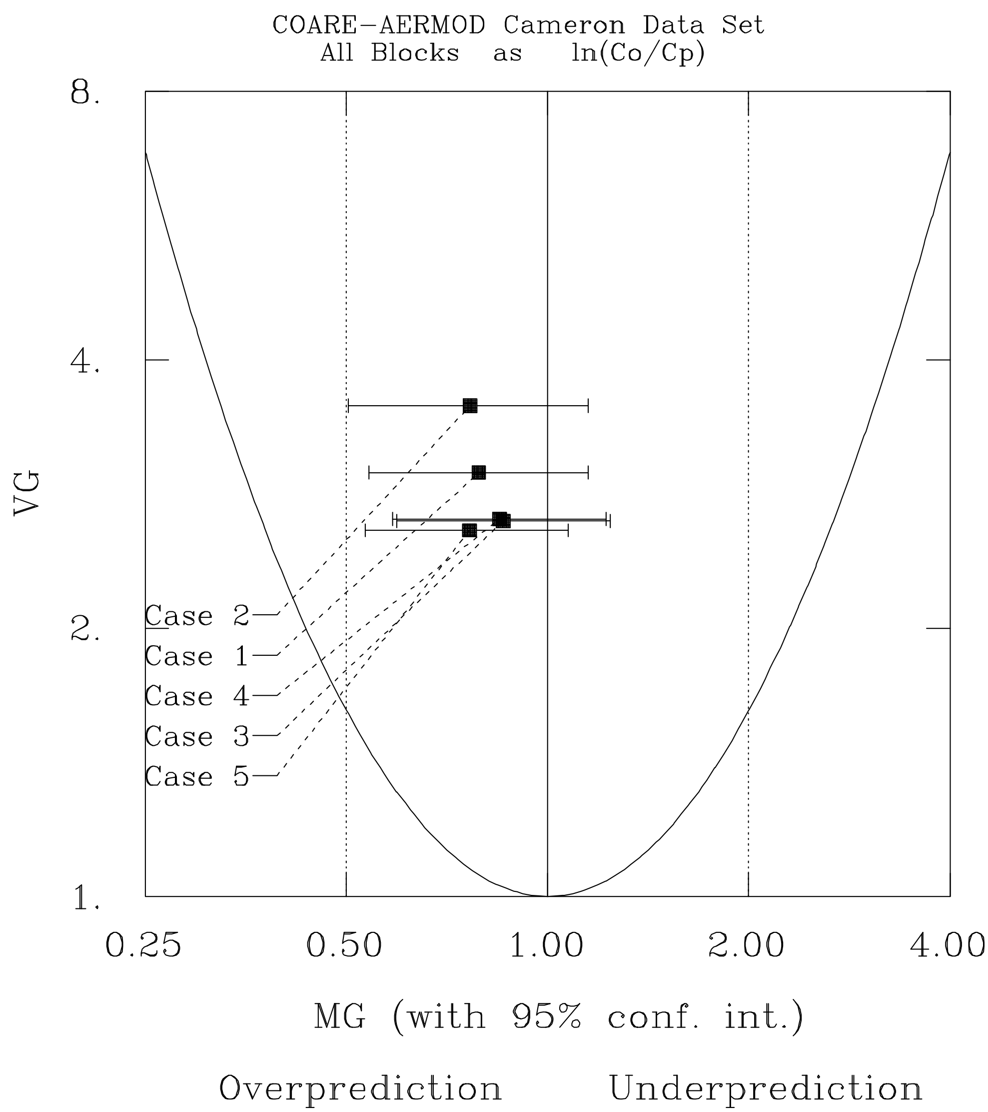
COARE−AERMOD Pismo Beach, Cameron & Carpinteria Data Sets
All Blocks as ln(Co/Cp)
8.
4.
2.
1.
VG
Case 2
Case 3
Case 1
Case 4
Case 5
0.25
0.50
1.00
2.00
4.00
MG (with 95% conf. int.)
Overprediction
Underprediction

Figure 21



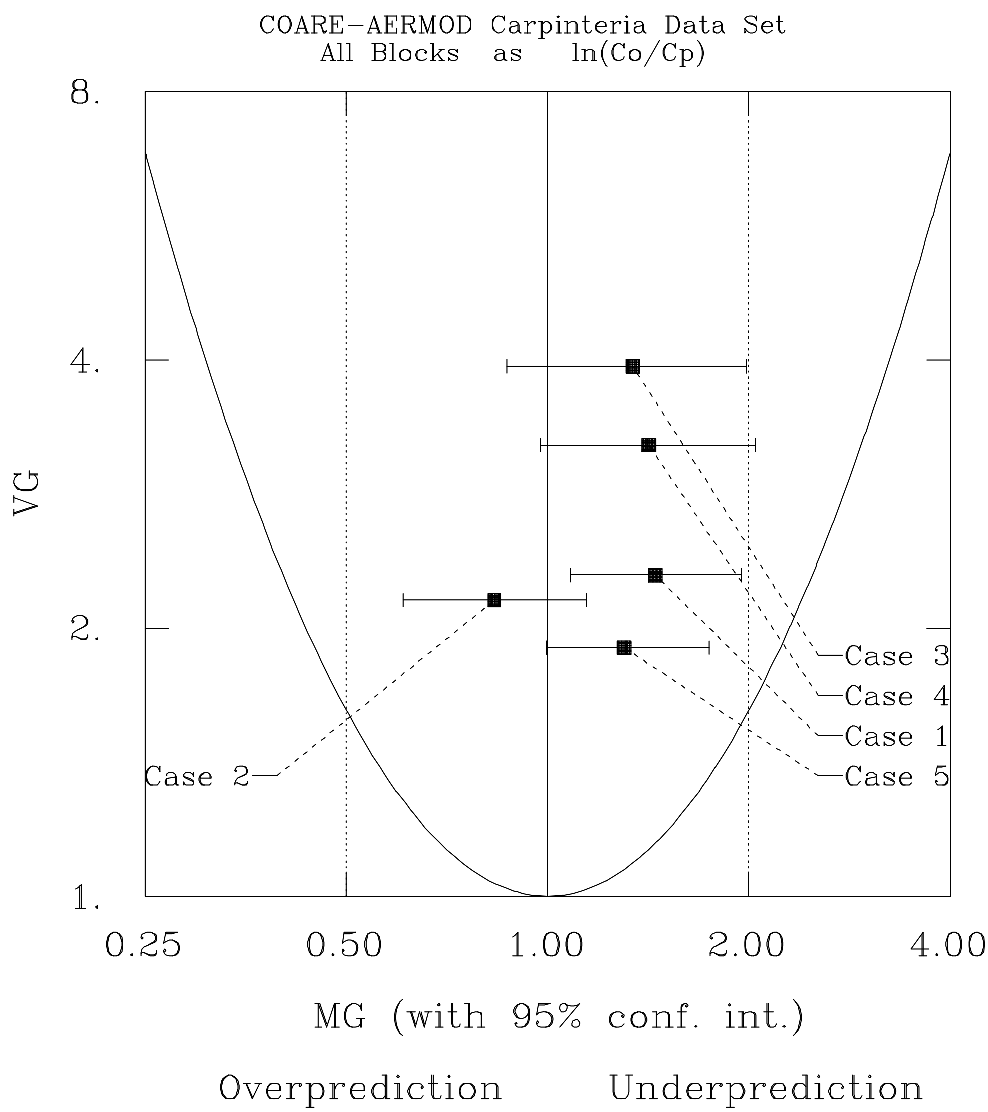
COARE-AERMOD Pismo Beach Data Set
All Blocks as ln(Co/Cp)
16.
8.
4.
2.
1.
VG
Case 2
Case 1
Case 4
Case 3
Case 5
0.25
0.50
1.00
2.00
4.00
MG (with 95% conf. int.)
Overprediction
Underprediction

Figure 22



COARE−AERMOD Cameron Data Set
All Blocks as ln(Co/Cp)
8.
4.
2.
1.
VG
Case 2
Case 1
Case 4
Case 3
Case 5
0.25
0.50
1.00
2.00
4.00
MG (with 95% conf. int.)
Overprediction
Underprediction

Figure 23


COARE–AERMOD Carpinteria Data Set
All Blocks as ln(Co/Cp)
8.
4.
2.
1.
VG
Case 3
Case 4
Case 1
Case 5
Case 2
0.25
0.50
1.00
2.00
4.00
MG (with 95% conf. int.)
Overprediction
Underprediction

Attachment 1: COARE-AERMOD Evaluation Files CD

Attachment 2: COARE Bulk Flux Algorithm Papers

COARE BULK AIR-SEA FLUX ALGORITHM

C. Fairall (NOAA/ERL)
E.F. Bradley (CSIRO)
D. Rogers (Scripps)

History

In 1993, Chris Fairall, Frank Bradley and David Rogers began development of a bulk air-sea flux algorithm for use by the COARE community. Based on the model of Liu, Katsaros and Businger (1979, LKB), it took account of the light wind, strongly convective conditions over tropical oceans. Version 1.0 was released in November 1993, and included modifications to the basic LKB code for wind roughness length (Smith, 1988), Monin-Obukhov profile functions for strong convection, and low-wind "gustiness" (Godfrey and Beljaars, 1991). Version 2.0 (August 1994) included code to model the cool skin physics (Saunders, 1967), and also daytime near-surface warming based on a simplified version of the Price, Weller and Pinkel (1986) ocean mixing model (Fairall et al., 1996a). These optional features enable conversion from bulk to true skin temperature for calculating the fluxes. Calculation of fluxes of momentum (Caldwell and Elliott, 1971) and sensible heat (Gosnell, Fairall and Webster, 1995) due to rainfall are incorporated in the code, as is the so-called Webb correction to latent heat flux which arises from the requirement that the net dry mass flux be zero (Webb et al., 1980). The formalism of the algorithm is fully described in Fairall et al. (1996b).

The last major modifications to the algorithm were made at the COARE Air-Sea Interaction (Flux) Group Workshop in Honolulu, 2-4 August 1995 (Bradley and Weller, 1995). Transfer coefficients were adjusted by six percent to give better average agreement with covariance latent heat fluxes from several COARE ships. This produced version 2.5b, which has been used successfully on various ocean-atmosphere field campaigns by members of the Flux Group, at various locations and from a variety of platforms. At the Woods Hole workshop, 9-11 October 1996 (Bradley and Weller, 1997) it was agreed that no further development would be attempted to the community version of the COARE Bulk Flux Algorithm, and that a version 2.5b bulk algorithm "package" would be made available, consisting of the fortran source code and a test data set. This was released at a meeting of the Flux Group at NCAR, 14-16 May 1997 (Bradley, Moncrieff and Weller, 1997):

Description of the bulk algorithm "package"

The "package" consists of three files:

coar2_5b.f 33K (Fortran source code)
test2_5b.dat 12K (Test data set)
test2_5b.out 14K (Output file from test data)

Fortran program

A full description of the code and the test data set appears at the head of the fortran file. We provide some notes here:

1. The input "read" statement is set up for the test data file test2_5b.dat . This consists of four days of Moana Wave COARE data, 26-29 Nov 1992, prepared from Chris Fairall's hourly data file wavhr2_5.asc dated 31/10/96. A full description of the Moana Wave operations, instruments and data set is given at: http://www.ncdc.noaa.gov/coare/catalog/data/air_sea_fluxes/moana_flux.html

2. Only those observations required by the flux algorithm were extracted from Chris' lines of data, excepting that his independently calculated bulk fluxes are included for comparison.

3. Some parameters are not input, but must be redefined in the code if necessary (e.g., the height of sensors (hum, htm), the bulk temperature sensor depth (ts_depth), needed for calculation of the warm layer effect, and pressure and mixed layer height (pp and zi) if available).

4. Because Chris' Tsea was measured at only 0.05m depth, we have added Ts at 6m depth from Mike Gregg's Advanced Microstructure Profiler (AMP, but called MSP in the file) to demonstrate the warm layer code. The Profiler was operated from the Moana Wave during leg 1, and the data was kindly provided in suitable form for the test file by Hemantha Wijesekera (Oceanography Dept., Oregon State University).

5. The warm layer and/or cool skin code may be bypassed by setting jwarm and/or jcool to zero in the code.

6. To demonstrate the warm layer and cool skin, we output the respective delta-temperatures and the warm layer thickness. Note that dt_warm is the warming across the entire warm layer--only if tk_pwp is less than the sensor depth (ts_depth = 6m in the test case) will T0=ts-dt_cool+dt_warm. Otherwise, a linear profile is assumed, and the appropriate fraction of warming above the bulk sensor calculated. Chris' Tsea at 0.05m depth will generally include most of the warm layer but not the cool skin effect.

7. The Webb correction to latent heat flux and the sensible heat flux due to rainfall are NOT added to these fluxes internally in the code. They are output separately, and may be accounted for at the user's discretion.

Test input file

```
Date:  YYMMDDHHmmss, YY=year, MM=month, DD=day, HH=hour, mm=minute,ss=sec
U:     true wind speed at 15-m height  m/s
Tsea:  sea surface temp (at about 0.05m depth)  deg.C
Tair:  Vaisala air temperature (about 15 m)  deg.C
qair:  Vaisala air specific humidity (about 15 m)  g/kg
Hsb:   Fairall's bulk sensible heat flux  W/m2
Hlb:   Fairall's bulk latent heat flux   W/m2
Taub:  Fairall's bulk surface stress  N/m2
Rs:    solar irradiance  W/m2
Rl:    downwelling longwave irradiance  W/m2
Rain:  precipitation mm/hr
Lat:   Latitude
Lon:   Longitude
MSP:   AMP temperature at 6m depth  deg.C
```

Test output file

```
index:  data line number
xtime:  YYMMDDHHmmss, date and time as read in
hsb:    Fairall's bulk sensible heat flux as read in  W/m2
hlb:    Fairall's bulk latent heat flux as read in   W/m2
taub:   Fairall's bulk surface stress as read in    N/m2
ts:     AMP temperature at 6m depth as read in (rounded)  deg.C
HF:     calculated sensible heat flux   W/m2
EF:     calculated latent heat flux    W/m2
TAU:    calculated surface stress   N/m2
T0:     calculated sea skin temperature   deg.C
Webb:   correction to latent heat flux (to be added)  W/m2
RainF:  sensible heat flux due to precipitation   W/m2
rain:   precipitation mm/hr as read in
dt_cool:  cool skin effect  deg.C
dt_warm:  total warming across warm layer thickness  deg.C
tk_pwp:   warm layer thickness  m
```

References

Bradley, E.F., and R.A. Weller, 1995: Third Workshop of the TOGA COARE Air-Sea Interaction (Flux) Working Group. Honolulu, 2-4 Aug 1995. UCAR/TCIPO. UCAR Communications, PO Box 3000, Boulder CO 80307-3000 USA.

Bradley, E.F., and R.A. Weller, 1997: Fourth Workshop of the TOGA COARE Air-Sea Interaction (Flux) Working Group. Woods Hole, 9-11 Oct 1996. UCAR/TCIPO. UCAR Communications, PO Box 3000, Boulder CO 80307-3000 USA.

Bradley, E.F, M.W. Moncrieff and R.A. Weller, 1997: Joint workshop of the TOGA COARE Flux and Oceans Working Groups, and the GEWEX GCSS Working Group 4. Boulder, Colorado, 14-16 May 1997. NCAR/MMM, PO Box 3000, Boulder CO 80307-3000 USA.

Caldwell, D.R. and W.H. Elliott, 1971: Surface stresses produced by rainfall, *J. Phys. Oceanog.* 1, 145-148.

Fairall, C.W., E.F. Bradley, J.S. Godfrey, G.A. Wick, J.B. Edson, and G.S. Young, 1996a: The cool skin and the warm layer in bulk flux calculations. *J. Geophys. Res.* 101, 1295-1308.

Fairall, C.W., E.F. Bradley, D.P. Rogers, J.B. Edson, G.S. Young, 1996b: Bulk parameterization of air-sea fluxes for TOGA COARE. *J. Geophys. Res.* 101, 3747-3764.

Godfrey, J.S., and Beljaars, 1991: *J. Geophys. Res.* 96, 22043-22048.

Gosnell, R., C.W. Fairall, and P.J. Webster, 1995: The sensible heat flux of rainfall in the tropical ocean. *J. Geophys. Res.* 100, 18437-18442.

Liu, W.T, K.B. Katsaros and J.A. Businger, 1979: Bulk parameterization of the air-sea exchange of heat and water vapor including the molecular constraints at the interface, *J. Atmos. Sci.* 36, 1722-1735.

Price, J.F., R.A. Weller and R. Pinkel, 1986: Diurnal cycling: Observations and models of the upper ocean response to diurnal heating, cooling, and wind mixing, *J. Geophys. Res.* 91, 8411-8427.

Saunders, P.M., 1967: The temperature at the ocean-air interface, *J. Atmos. Sci.* 24, 269-273.

Smith, 1988: *J. Geophys. Res.* 93, 15467-15472.

Webb, E.K., G.I. Pearman and R. Leuning, 1980: Correction of flux measurements for density effects due to heat and water vapour transfer, *Q.J.R. Meteorol. Soc.* 106, 85-100.

For more information, please contact:

Chris Fairall
NOAA/ERL/WPL
325 Broadway
Boulder, CO 80303 USA
e-mail: cwf@etl.noaa.gov
Phone: (303)497-3253
Fax: (303)497-6978

OR

E. Frank Bradley
CSIRO
Centre for Environmental Mechanics
GPO Box 821
Canberra, ACT 2601 AUSTRALIA
e-mail: bradley@enmech.csiro.au
Phone: (61) 62 46 5575
Fax: (61) 62 46 5560

OR

David P. Rogers
Scripps Institution of Oceanography
La Jolla, CA 92093-0230 USA
e-mail: drogers@ucsd.edu
Phone: (619) 534-6412
Fax: (619) 534-7452

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COARE BULK FLUX ALGORITHM VERSION 2.0 10 August 1994

C.W. Fairall
R/E/ET7
NOAA/ERL
325 Broadway
Boulder, CO 80303 USA
Tel: 303-496-3253
FAX: 303-497-6978
EMAIL: C.Fairall@omnet.com

I. Background

The COARE 2.0 algorithm was developed by C.Fairall, E.F.Bradley, and D.Rogers. Details are doccumented in papers on the algorithm (Fairall et al., 1994a) and the cool skin and warm layer effects (Fairall et al., 1994b). The algorithm is designed to give estimates of the turbulent fluxes of sensible and latent heat and the stress from inputs of bulk variables. The bulk transfer coefficients are based on the Liu, Katsaros, Businger model (JAS, 36, 1722, 1979) with some modifications.

II. COARE version 1.0

Version 1.0 was released in November, 1993. It contained the following modifications to the basic LKB code:

1. Sea surface humidty, Qs, was expressed as 0.98 times the saturation humidity of pure water at the sea surface temperature. This was done to account for the reduction in water vapor pressure by salinity in sea water.

2. The velocity roughness length was specified as the sum of a Charnock formula and a smooth flow limit as per Smith (JGR, 93, 15467, 1988)

```
zo = 0.011 u*^2/g + 0.11 nu/u*
```

where u* is the friction velocity, g the acceration of gravity, and nu the kinematic viscosity of air.

3. The Monin-Obukhov dimensionless profile functions were given a form that asymptotically approached the proper convective limit as wind speed goes to zero. As stability approaches neutral conditions, the function is blended to a standard Kansas type.

4. The von Karmon constant is set to k=0.4 and dimensionless scalar gradients have a value of 1.0 at neutral conditions.

5. The LKB specification of temperature and moisture roughness lengths (Rt and Rq) in terms of velocity roughness Reynolds number, Rr, were retained but the transfer coefficients for moisture and heat were reducted 15%. This adjustment was done to give better average agreement with the Moana Wave flux data from COARE. In the original LKB paper one finds

```
SQRT(Ctn) = (1/2.2) / ln(z/zot)
```

This was changed to

```
SQRT(Ctn) = (1/2.2/1.15) / ln(z/zot)
```

6. Following Godfey and Beljaars (JGR, 96, 22043, 1991), the wind speed in the bulk expression is augmented by a gustiness velocity, Wg

```
u = sqrt[Ux^2  +  Uy^2 + Wg^2]
```

where Ux and Uy are the mean wind components (i.e., magnitude of the mean wind vector) and Wg is proportional to the convective scaling velocity, W*

```
Wg = beta W*
```

A value for beta of 1.2 was chosen based on the Moana Wave data.

III. COARE version 2.0

Version 2.0 was released at the COARE data workshop in Toulouse, France, in August of 1994. It contained the following changes to the 1.0 version.

1. The specification of Rt and Rq was changed slightly in the Rr range from 0.13 to 1.0. The basic transfer coefficient expression became

```
SQRT(Ctn) = k/ln(z/zot)
```

2. A cool skin model was added to correct bulk water temperatures to true SST. This model was based on the standard Saunders type (JAS, 24, 269, 1967) with a modification to include the effects of buoyancy flux. This produces a cool skin of about 0.3 K during the night. During the day the cool skin may be reduced or eliminated entirely by solar heating in the upper mm of the ocean.

3. A warm layer model was added to correct bulk water temperature measurements made at some depth, Zb. The idea is that ship intake and buoy temperature sensors at a meter or so depth are unable to resolve the

diurnal warm layer common in the COARE region under light wind conditions. This model was based on a simplified scaling version of the Price Weller Pinkel mixing model (JGR, 91, 8411, 1986). If daytime solar heating is sufficient, a stable near-surface layer is formed causing the surface temperature to increase. Linear profiles of temperature and current are assumed. The depth is determined by a critical Richardson number (Ri) and the profile of absorption of solar energy in the water. Ri is set to 0.65 as per PWP. Under very light wind conditions, peak solar warming as great as 4 K is produced with a warm layer depth of about 0.25 m. Once the warm layer forms, its depth and intensity are determined by integrating the accumulated momentum and heat input in the layer. Thus, this model requires a complete time series of data throughout the diurnal cycle.

Both the cool skin and warm layer can be switched off if true surface temperature is available (e.g., from aircraft with IR thermometers).

4. The heat flux due to precipitation is estimated as per Gosnell et al. (1994).

IV. Inputs and Outputs

COARE version 2.0 requires the following inputs:

1. General inputs
   - Measurement heights for wind speed, air temperature, humidity
   - Measurement depth for water temperature
   - Switch setting for cool and warm layers (Jcool, Jwarm)
   - Longitude or time zone of experiment
   - Atmospheric inversion height (default 600 m)
   - Atmopsheric surface pressure (mb)
   - Reference heights for output means

2. Line inputs
   - Wind vector magnitude (m/s)
   - Water temperature (Cel)
   - Air temperature (Cel)
   - Humidity: either specific humidity (g/kg) or RH (0 to 1.0)
   - Downward solar flux (W/m^2)
   - Downward IR flux (W/m^2)
   - Precipitation rate (mm/hr)

Note if downward solar is not known, it can be estimated with standard models if cloud information is available. Also, if downward IR is not available, it can be estimated as 420 W/m^2 for the COARE area; or, a bulk model can be used.

The model outputs values for the turbulent fluxes, rain heat flux, warm and cool layers, plus numerous diagnostic variables such as transfer coefficients and roughness lengths. Also, the mean data can be extrapolated to some reference height (e.g, 10-m) specified at the beginning. This is useful for comparing measurements made at different heights (e.g., buoy and aircraft).

Fortran (77.f) and Rocky Mountain Basic versions are available. Also, a set of Fotran programs for driving MATLAB are also available. Additional programs for the inertial-dissipation flux method and Payne's albedo code are available.

V. Comments on surface energy budget.

The COARE flux working group recommends the following:

1. Sea surface broadband IR emissivity of 0.97.

2. Average sea surface albedo of 0.055 (otherwise use Payne).

3. Wind speeds should be referenced to the sea surface. In other words, GPS winds should be corrected for surface currents.

4. Rain is 0.2 K cooler than the droplet wetbulb temperature.

5. The time scale of the average bulk variables used in this algorithm is on the order of 30 minutes. The use of daily averaged or monthly averaged variables is not recommended.

6. Measurement heights greater than 50 m should be put in as 50 m.

THE TOGA-COARE BULK AIR-SEA FLUX ALGORITHM
September 2, 2003

C. W. Fairall (NOAA/ERL/ETL, Boulder, USA)
E.F. Bradley (CSIRO Land and Water, Canberra, Australia)

History

The international TOGA-COARE field program took place in the western Pacific warm pool over 4 months from November 1992 to February1993. Development of a bulk air-sea flux algorithm for use by the COARE community began almost immediately. Based on the model of Liu, Katsaros and Businger (1979, LKB), it took account of the light wind, strongly convective conditions over tropical oceans. **Version 1.0** was released in November 1993, and included modifications to the basic LKB code for wind roughness length (Smith, 1988), Monin-Obukhov profile functions for strong convection, and low-wind "gustiness" (Godfrey and Beljaars, 1991). **Version 2.0** (August 1994) included code to model the ocean cool skin physics (Saunders, 1967), and also daytime near-surface warming based on a simplified version of the Price, Weller and Pinkel (1986) ocean mixing model (Fairall et al., 1996a). These optional features enabled conversion from bulk to true skin temperature for calculating the fluxes. Calculation of fluxes of momentum (Caldwell and Elliott, 1971) and sensible heat (Gosnell, Fairall and Webster, 1995) due to rainfall were incorporated in the code, as was the so-called Webb correction to latent heat flux which arises from the requirement that the net dry mass flux be zero (Webb et al., 1980). The formalism of this version of the algorithm was fully described in Fairall et al. (1996b).

A major modification to the algorithm was made at a COARE Air-Sea Interaction (Flux) Group Workshop (Bradley and Weller, 1995). Transfer coefficients were reduced by six percent to give better average agreement with covariance latent heat fluxes from several COARE ships. This **version 2.5**, was used successfully on ocean-atmosphere field campaigns by members of the Flux Group, at various locations and from a variety of platforms. At the following workshop (Bradley and Weller, 1997) it was agreed that, after minor faults were corrected, a **version 2.5b** COARE bulk algorithm "package", consisting of the Fortran source code, a test data set, and the corresponding computed flux results, would be made generally available. This was released at the final Flux Group workshop (Bradley, Moncrieff and Weller, 1997), and available from several archive sites. Shortly after, a Matlab version was posted on the ETL web site.

Version 2.5b had been developed using COARE measurements exclusively, which were limited to wind speeds in the range 0-12 ms^{-1} and the tropical environment. Nevertheless, the algorithm was frequently applied beyond these limits, including by the authors. Between 1997 and 1999 the NOAA/ETL air-sea interaction database expanded with directly measured covariance and inertial dissipation fluxes from cruises at higher latitudes and in stronger winds. This enabled further development of the COARE algorithm (Bradley et al. 2000, Fairall et al. 2001). In January 2000 **version 2.6a** was posted in both Fortran and Matlab codes. It was updated in June 2001 with **version 2.6bw**, which included the option to calculate momentum roughness lengths using surface gravity wave information. At this stage, with little further modification to either physics or parameterizations, the formalism of the algorithm was published (Fairall et al. 2003), as version 3.0a at the suggestion of a reviewer who felt the advances over 2.5b warranted this.

Significant differences between versions 3.0a and 2.5b

COARE 2.5 versions were based on concepts and empirical relationships carried over from LKB, modified as described in Fairall et al. (1996b) on the basis of about 800 hours of quality controlled eddy-flux measurements on Moana Wave during the COARE IOP. These were mostly for wind speeds less than $10ms^{-1}$. For versions 2.6 and 3.0, transfer coefficients were obtained using a dataset which combined COARE data with those from three other ETL field experiments, and a reanalysis of the HEXMAX data (DeCosmo et al. 1996). This extended the range to around $20ms^{-1}$. The algorithm thus formulated was then validated against a covariance flux database containing 7216 hours of data from all ETL cruises to 1999, including about 800 hours with wind speeds exceeding $10ms^{-1}$ and 2200 hours at high latitudes (Fairall et al. 2003).

Specific changes are:

1. The empirical constants in the convective portion of the profile functions have been changed for improved matching to direct profile observations (Grachev et al. 2000).

2. The Kansas stable profile functions (Businger et al. 1991) have been replaced by those from Beljaars and Holtslag (1991) which, based on new profile data taken over the Arctic ice cap (Persson et al. 2002), appear to be a better fit at extreme stability.

3. A fixed value of the Charnock parameter (α=0.011) has been replaced by one with a simple wind-speed dependence above 10 ms^{-1} based on data from various sources (e.g. Hare et al. 1999). See Fairall et al. (2003), figure 1.

4. The scalar roughness parameters (zot, zoq) were previously obtained using the LKB relationships between roughness Reynolds number (Rr) and its scalar analogues (Rt, Rq). They are now calculated directly as $zoq=zot=min(1.15e^{-4}, 5.5e^{-5}/Rr^{0.6})$, which fits the ETL and HEXMAX data sets (see Fairall et al. 2003, figure 4). The moisture and heat transfer coefficients are now identical and slightly reduced at low winds.

5. The stability iteration loop has been reduced from 20 to 3 by taking advantage of a bulk Richardson number parameterization for an improved first guess (Grachev and Fairall 1997).

6. The latent heat flux has been reformulated in terms of mixing ratio, q, instead of water vapor density, Q, because q is the quantity that is fundamentally conserved during mixing. This eliminates the need for a Webb et al. (1980) correction; however we now return the mean Webb vertical velocity which may be used for correction of trace gas or particle fluxes measured simultaneously.

7. In the cool skin calculation, the Saunders coefficient (xlamx) limit has been reduced from 30 to 6 in the 'warm skin' regime to eliminate unreasonable values in very light winds. The cool skin thickness has been capped to prevent excessive thickness under very stable conditions

8. Optional code has been added to account for the effects of surface gravity waves on the velocity roughness, and hence the momentum transfer coefficient. We use either the wave age parameterization of Oost et al. (2002), or the model of Taylor and Yelland (2001) which parameterizes surface roughness in terms of the significant wave height and peak wavelength. This feature would allow the algorithm to be applied, for example, in coastal/shallow waters and is partly in response to requests from some users. It has not been evaluated by the authors, who would welcome feedback.

9. The date is input in Y2K format (YYYY instead of YY).

The bulk algorithm "package"

The "package" consists of an input data file, the bulk algorithm program, and output data files to be found on ftp://ftp.etl.noaa.gov/et7/users/cfairall/bulkalg/cor3_0:

Input data

test3_0.txt (Test data set, without headers, tab delimited)

Programs

cor3_0af.for (fortran source code) and *.m* (matlab source code). This version is set up to use the Fairall near-surface temperature sensor for Ts bulk.

cor3_0ah.for (fortran source code) and *.m* (matlab source code). This version is setup to use the MSP 6m-depth temperature sensor for Ts bulk.

Output files

tst3_0af.out and *tst3_0ah.out* Fortran output files from test data

tst30afo.out and *tst30aft.out* Fortran output files with waves (jwave=1 or 2)

tst3_0af_out.txt Matlab output file from test data

tst3_0afo_out.txt and *tst3_0aft_out.txt* Matlab output file files with waves (jwave=1 or 2)

Files with *.mat are in Matlab matrix format

Fortran program

Brief notes about the algorithm and the test data set appears at the head of the fortran file. Here we provide some comments on the structure of the code:

1. The input "read" statement is set up for the test data file test3_0.txt . This consists of four days of Moana Wave COARE data, 26-29 Nov 1992, prepared from Chris Fairall's hourly data file wavhr2_5.asc dated 31/10/96. A full description of the Moana Wave operations, instruments and data set is given at http://www.ncdc.noaa.gov/coare/catalog/data/air_sea_fluxes/moana_flux.html

2. A list of input variables is given, with units etc.. Only the first 11, the critical environmental and position variables, appear in the test data. If time series of p and/or zi are available to the user, they may be added to the “700 read…” input string, and the default values disabled. The remaining input parameters relate to the instrument set-up and are expected to remain fixed for the duration of the observations. They are therefore set in the main program, as are the switches for cool skin, warm layer and wave state options.

3. Properly, wind speed should be relative to the water surface. “u” should be the vector sum of measured wind speed and surface current if available, calculated by the user outside the program.

4. Two sea temperature measurements are given in the test data, one at only 0.05m depth, the other at 6m from Mike Gregg's Advanced Microstructure Profiler which operated from the Moana Wave during leg 1. The data was kindly provided in suitable form by Hemantha

Wijesekera (COAS, OSU). It allows a better demonstration of the calculation of skin temperature from the bulk via the warm layer option. "ts_depth" should be set to correspond with whichever of "ts" or "hwt" is selected.

5. If skin temperature (sst) is measured directly with an infra-red radiometer, the warm layer and cool skin codes should be bypassed by setting jwarm and jcool to zero

6. jwave selects the method of calculating zo at the beginning of the main iteration loop in subroutine(ASL), i.e. Smith (1988) or one of the two wind/wave parameterizations. The latter require values for the significant wave height (hwave) and dominant wave period (twave), which are calculated in the code from formulas given by Taylor and Yelland (2001) for fully developed seas. If measurements of hwave and twave are available, they should be added to the input data string and the default values disabled.

7. Structure of the fortran code.

The main program (**fluxes**) opens the input and output files, reads the data and sets fixed values, defaults and options. It adds a data line number (index) and calls subroutine **bulk_flux**, passing input data in COMMON.

Bulk_flux defines most physical constants and coefficients and, after determining the proper conditions, calculates and integrates the diurnal warming of the ocean surface, using fluxes and net longwave radiation from the previous time-step and the solar absorption profile. The fraction of warming above the temperature sensor is added to the measurement, and subroutine **ASL** is called for the flux and boundary layer calculations.

ASL is a descendant of the original LKB code, but almost all operations and parameterizations are changed. After a series of first guesses and operations to characterize the atmospheric surface layer within the framework of Monin-Obhukov similarity theory, the core of the subroutine is an iteration loop. This iterates three times over the fluxes (in the form u*, t*, q*), the roughness parameters (zo, zot, zoq), the M-O stability parameter and profile phi functions, and also calculates gustiness and the cool skin within the loop. Final values are returned to **bulk_flux** in COMMON.

Finally, **bulk_flux** calculates the surface fluxes (Wm^{-2}), skin temperature (sst), heat and momentum fluxes due to rainfall, neutral transfer coefficients, values of state variables at standard height, etc., and saves the fluxes for the next timestep warm layer integrals. Output files are written before returning to the main program for the next line of input data.

8. Outputs available from **bulk_flux** are listed at the head of the program. The outputs in tst3_0af.out are given below. To illustrate the warm layer and cool skin, we output the respective delta-temperatures and layer thicknesses. Note that dt_warm is the temperature across the entire warm layer. Only if tk_pwp is less than the sensor depth (ts_depth = 6m in the test case) will tsw=ts +dt_warm. Otherwise, a linear profile is assumed, and the warming above the bulk sensor calculated. The measurement of "ts" at 0.05m depth will generally include most of the warm layer but not the cool skin effect.

Matlab programs

cor3_0af .m and *cor3_0ah .m*

Read the data, do the warm layer calculations, draw some graphs, write the new files

Call the flux and cool skin subroutine *cor30a.m*

This routine operates on the data vector

```
x=[u us ts t qs q Rs Rl rain zi  P zu zt zq lat jcool jwarm jwave twave
hwave]
```

and returns a long data vector of 22 quantities described at the end of the routine. Other subroutines used: psiu_30.m, psit_30.m, qsee.m, grv.m

These versions of the test code save a huge time series matrix of variables (including the first 9 components of the original input, the output vector y, and several other quantities of interest) in the parameter *dt*. This matrix can be saved for subsequent applications. Note: if you are not interested in the warm layer, then fluxes can be computed by calling *cor30a*(x) as a simple function.

Structure of *cor3_0ax.m* (by line numbers)

0-60	Descriptions, comments, etc.
63-82	Read in test data set, input to variable names
84-92	Set sensor heights, depth; set calculation condition parameters (cool skin, etc)
94-107	Initialize variables
108-121	Set various physical constants
126-315	Main data processing loop
127-131	Set P, us, and zi (could be part of input string but aren't in the test data
135-155	Rename input matrix variables into single variables
156-173	Compute physical parameters (e.g., net IR radiative flux) for warm layer routine
175	Check to see if warm layer calculation is active
176-239	Warm layer calculations
240-244	Add warm layer to bulk Ts
245-248	Compute equilibrium wave properties
249-252	Set the bulk x vector and call cor30a
253-282	Extract bulk flux and cool skin variables
283-291	Compute extra variables and save in *dt* matrix
292-308	Input results to *out* matrix (for later file write)
309-314	Preserve flux results to pass forward for next warm layer cycle
314	increment loop counter
315	End main calculation loop
316-319	Plot results
321-332	Print output file

Structure of *cor30a.m*

2-7	Comments
8-26	Pass x vector to name variables
28-50	Set constants and compute physical parameters
51-58	Compute wave and net radiative parameters
61-78	Compute initial guess for transfer coefficients and roughness length
79-95	Compute first guess scaling parameters, select number of iterations required

97-105	Compute Charnock parameter from 10-m wind speed
109-151	Stability and cool skin loop
111	Compute zet from previous u*, q*, T* values
114-123	Compute new values for roughness and scaling parameters
124-130	Compute gustiness
131-137	Compute various heat fluxes for cool skin
138-149	Compute cool skin
151	End main iteration loop
152-156	Compute basic fluxes
157-162	Compute rain heat flux
163-174	Compute Webb velocity and various transfer coefficients

Test input file *test3_0.txt*

1 Date: YYYYMMDDHHmmss.ss, YYYY=year, MM=month, DD=day, HH=hour, mm=minute,ss.ss=sec
2 U: true wind speed at 15-m height m/s corrected for surface currents
3 Tsea: sea surface temp (at about 0.05m depth) deg.C
4 Tair: Vaisala air temperature (about 15 m) deg.C
5 qair: Vaisala air specific humidity (about 15 m) g/kg
6 Rs: solar irradiance W/m2
7 Rl: downwelling longwave irradiance W/m2
8 Rain: precipitation mm/hr
9 Lat: Latitude (N=+)
10 Lon: Longitude (E=+)
11 MSP: MSP temperature at 6m depth deg.C

Test output files *tst3_0af.out* and *tst3_0ah.out*

1 index: data line number
2 xtime: YYYYMMDDHHmmss, date and time as read in (without dec. sec.)
3 hf: sensible heat flux W/m2
4 ef: latent heat flux W/m2
5 sst: sea skin temperature deg.C
6 tau: surface stress N/m2
7 Wbar: mean Webb vertical velocity m/s
8 rf: sensible heat flux due to precipitation W/m2
9 dter: cool skin effect deg.C
10 dt_wrm: warming across entire warm layer deg.C
11 tk_pwp:warm layer thickness m
12 tkt*1000:tkt=cool skin thickness
13 Wg: gustiness velocity m/s

The Matlab and Fortran codes output data files are in the same format. The outputs of the programs have been compared and differ by less than 0.1% for fluxes. As an example, the time series of latent heat flux is shown below.

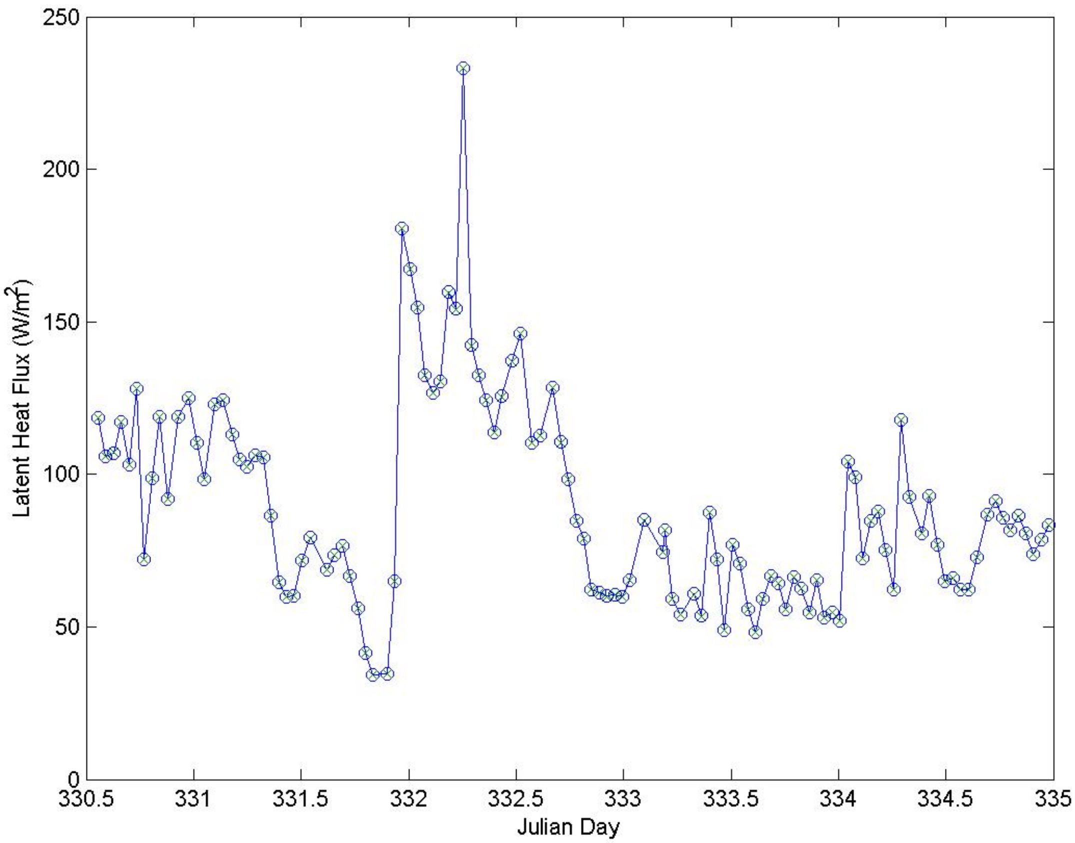

Figure 1. Time series of latent heat flux from the Matlab and Fortran versions of the COARE3.0 algorithm using the test data set. The circles are the matlab values and the x's are the Fortran values.

References

Beljaars, A. C. M., and A. A. M. Holtslag, 1991: Flux parameterization over land surfaces for atmospheric models. *J. Appl. Meteor.*, **30**, 327-341.

Bradley, E.F., and R.A. Weller, 1995: Third Workshop of the TOGA COARE Air-Sea Interaction (Flux) Working Group. Honolulu, 2-4 Aug 1995. UCAR/TCIPO. UCAR Communications, PO Box 3000, Boulder CO 80307-3000 USA.

Bradley, E.F., and R.A. Weller, 1997: Fourth Workshop of the TOGA COARE Air-Sea Interaction (Flux) Working Group. Woods Hole, 9-11 Oct 1996. UCAR/TCIPO. UCAR Communications, PO Box 3000, Boulder CO 80307-3000 USA.

Bradley, E.F, M.W. Moncrieff and R.A. Weller, 1997: Joint workshop of the TOGA COARE Flux and Oceans Working Groups, and the GEWEX GCSS Working Group 4. Boulder, Colorado, 14-16 May 1997. NCAR/MMM, PO Box 3000, Boulder CO 80307-3000 USA.

Caldwell, D.R. and W.H. Elliott, 1971: Surface stresses produced by rainfall. J. Phys. Oceanog. 1, 145-148.

DeCosmo, J., K. B. Katsaros, S. D. Smith, R. J. Anderson, W. A. Oost, K. Bumke, and H. Chadwick, 1996: Air-sea exchange of water vapor and sensible heat: The Humidity Exchange Over the Sea (HEXOS) results. J. Geophys. Res., 101, 12001-12016.

Fairall, C.W., E.F. Bradley, J.S. Godfrey, G.A. Wick, J.B. Edson, and G.S. Young, 1996a: The cool skin and the warm layer in bulk flux calculations. J. Geophys. Res. 101, 1295-1308.

Fairall, C.W., E.F. Bradley, D.P. Rogers, J.B. Edson, G.S. Young, 1996b: Bulk parameterization of air-sea fluxes for TOGA COARE. J. Geophys. Res. 101, 3747-3764.

Fairall, C.W., E.F. Bradley, J.E. Hare, A.A. Grachev, and J.B. Edson, 2003: Bulk parameterization of air-sea fluxes: Updates and verification for the COARE algorithm. J. Climate 16, 571-591.

Godfrey, J.S., and Beljaars, 1991: On the turbulent fluxes of buoyancy, heat, and moisture at the air-sea interface at low wind speeds. J. Geophys. Res. 96, 22043-22048.

Gosnell, R., C.W. Fairall, and P.J. Webster, 1995: The sensible heat flux of rainfall in the tropical ocean. J. Geophys. Res. 100, 18437-18442.

Grachev, A.A., and C.W. Fairall, 1997: Dependence of the Monin-Obukhov stability parameter on the bulk Richardson number for unstable conditions over the ocean. *J. Appl. eteorol.*, **36**, 406-414.

Grachev, A. A., C. W. Fairall, and E. F. Bradley, 1999: Convective profile constants revisited. *Bound.-Layer Meteorol*., **94**, 495-515.

Hare, J. E., P.O.G. Persson, C. W. Fairall, and J. B. Edson, 1999: Behavior of Charnock's relationship for high wind conditions. Proc. 13th Symposium of Boundary Layers and Turbulence. AMS. Dallas, TX, Jan. 15-20, paper 5B.8.

Liu, W.T, K.B. Katsaros and J.A. Businger, 1979: Bulk parameterization of the air-sea exchange of heat and water vapor including the molecular constraints at the interface, J. Atmos. Sci. 36, 1722-1735.

Price, J.F., R.A. Weller and R. Pinkel, 1986: Diurnal cycling: Observations and models of the upper ocean response to diurnal heating, cooling, and wind mixing, J. Geophys. Res. 91, 8411-8427.

Saunders, P.M., 1967: The temperature at the ocean-air interface. J. Atmos. Sci. 24, 269-273.

Smith, 1988: Coefficients for sea surface wind stress, heat flux, and wind profiles as a function of wind speed and temperature. J. Geophys. Res. 93, 15467-15472.

Webb, E.K., G.I. Pearman and R. Leuning, 1980: Correction of flux measurements for density effects due to heat and water vapour transfer, Q.J.R. Meteorol. Soc. 106, 85-100.

Yelland, M. and P. K. Taylor, 1996: Wind stress measurements from the open ocean. *J. Phys. Oceanogr.*, **26**, 541-558.

For more information, please contact:

Chris Fairall
NOAA/ERL/ETL
325 Broadway
Boulder, CO 80303 USA
e-mail: chris.fairall@.noaa.gov
Phone: +1 303 497-3253
Fax: +1 303 497-6101

OR

Frank Bradley
CSIRO Land and Water
GPO Box 1666
Canberra, ACT 2601 AUSTRALIA
e-mail: frank.bradley@ csiro.au
Phone: +61 2 6246 5575
Fax: +61 2 6246 5560

Attachment 3: COARE Meteorological Data Road MAP

Cameron Met. Data

Common Analysis for all Cases:

Input variables to COARE

Name	Description	Source or Value
	Latitude	29.9
	Longitude	-93.3
	Mix. Ht. For Gustiness Calc	-999 (dummy value, COARE uses 600m)
u(m/s)	Wind speed (m/s)	Tracer Experimental Data
tseaC	Temp. of Sea Surface (°C)	Tracer Experimental Data except when inconsistent with temperature gradient data, then calculated from temp. measurement height and temperature gradient
tairC	Air Temp. (°C)	Tracer Experimental Data
RH(%)	Relative Humidity (%)	Tracer Experimental Data
PresMb	Pressure (mb)	1000 for all hours (OCD default)
rsW/m2	Solar radiation (W/m^2)	0 for all hours
tsky	Sky cloud cover (tenths)	0 for all hours
Ceil(100ft)	Ceiling Height (100's ft)	888 for all hours
Rain(mm)	Rainfall (mm/h)	0 for all hours
hwaveM	Not used	not used -999 for all hours
twaveS	Not used	not used -999 for all hours
zws	Ht. of wind sensor (m)	10 or 18 from tracer experiment data
ztemp	Ht. of temp. sensor (m)	10 or 18 from tracer experiment data
zrh	Ht. of RH sensor (m)	10 or 18 from tracer experiment data
ts_depth	Depth of sea surface meas. (m)	0.5 for all cases

Output Variables from COARE

Symbol	Description	Units
hf	Sensible heat flux	W/m^2
ef	Latent heat flux	W/M^2
sst	Skin temperature (sst = tsea - dter + dsea)	Deg. C
tau	Wind stress	N/m^2
Wbar	Webb mean vertical velocity	m/s
rf	Relative humidity	%
dter	cool skin temperature difference	Deg C
dt_wrm	total warm layer temperature difference	Deg C

tk_pwp	thickness of warm layer	M
tkt*1000.	cool skin thickness	mm x 1000
Wg	gustiness factor	m/s
usr	M-O velocity scaling parameter u* = friction velocity	m/s
tsr	M-O temperature scaling parameter t*	Deg C
qsr*1000	M-O humidity scaling parameter q*	kg/kg
xmol	Obukov Length	M
zo	Velocity roughness length	M
zot	Temperature roughness length	M
zoq	Humidity roughness length	M

Analysis Specific to Cases:

		Case1	Case 2	Case 3	Case 4	Case 5
Name		aermod_venk	aermod_nosigma	aermod	aermod_5L	aermod_drax
.sfc file		cameron_venk.sfc	cameron_venk.sfc	cameron_5L.sfc	cameron.sfc	cameron_venk.sfc
.pfl file		cameron.pfl	cameron_nosigma.pfl	cameron.pfl	cameron.pfl	cameron.pfl
Sigma Θ		measured	predicted	measured	measured	measured
Obukhov		>5	>5	>1	>5	>5
Lateral Dispersion		aermod	aermod	aermod	aermod	draxler
Mix Hts.		Venketram >25	Venketram >25	Observed	Observed	Venketram >25

.SFC file:

yr	year	81 or 82	81 or 82	81 or 82	81 or 82	81 or 82
mo	month	July or February	July or February	July or February	July or February	July or February
dy	day	Varies	Varies	Varies	Varies	Varies
jday	Julian Day	Varies	Varies	Varies	Varies	Varies
hr	Hour	Varies	Varies	Varies	Varies	Varies
SHF	Sensible Heat Flux (W/m^2)	COARE Output Does not vary from Case to Case	COARE Output Does not vary from Case to Case	COARE Output Does not vary from Case to Case	COARE Output Does not vary from Case to Case	COARE Output Does not vary from Case to Case
ustar	surface friction velocity (m/s)	Ustar from COARE is multiplied by $(L_{mod}/L_{COARE})^{1/3}$ (see L disc. Below)	Ustar from COARE is multiplied by $(L_{mod}/L_{COARE})^{1/3}$ (see L disc. Below)	Ustar from COARE is multiplied by $(L_{mod}/L_{COARE})^{1/3}$ (see L disc. Below)	Ustar from COARE is multiplied by $(L_{mod}/L_{COARE})^{1/3}$ (see L disc. Below)	Ustar from COARE is multiplied by $(L_{mod}/L_{COARE})^{1/3}$ (see L disc. Below)
wstar	Convective velocity scale (m/s)	Not used for stable cases. If Unstable = $[(u^*)(Z_{i\text{-}conv})/(0.4L)]^{1/3}$ note u* is modified as above	Not used for stable cases. If Unstable = $[(u^*)(Z_{i\text{-}conv})/(0.4L)]^{1/3}$ note u* is modified as above	Not used for stable cases. If Unstable = $[(u^*)(Z_{i\text{-}conv})/(0.4L)]^{1/3}$ note u* is modified as above	Not used for stable cases. If Unstable = $[(u^*)(Z_{i\text{-}conv})/(0.4L)]^{1/3}$ note u* is modified as above	Not used for stable cases. If Unstable = $[(u^*)(Z_{i\text{-}conv})/(0.4L)]^{1/3}$ note u* is modified as above
VPTG	Vertical potential temperature gradient above PBL (°C/m)	Set = 0.01 for all cases	Set = 0.01 for all cases	Set = 0.01 for all cases	Set = 0.01 for all cases	Set = 0.01 for all cases
Zi (Conv)	Convective Mixing Height (m)	Not used for stable cases. If unstable use value from tracer study (source unknown).	Not used for stable cases. If unstable use value from tracer study (source unknown).	Not used for stable cases. If unstable use value from tracer study (source unknown).	Not used for stable cases. If unstable use value from tracer study (source unknown).	Not used for stable cases. If unstable use value from tracer study (source unknown).

Zi (mech)	Mechanical Mixing Height (m)	$2300(u^*)^{1.5}$ limited to at least 25 m note u* is modified as above	$2300(u^*)^{1.5}$ limited to at least 25 m note u* is modified as above	Used Experiment Reported values for $Z_{i\text{-mech}}$ (source unknown)	Used Experiment Reported values for $Z_{i\text{-mech}}$ (source unknown)	$2300(u^*)^{1.5}$ limited to at least 25 m note u* is modified as above
L	Monin-Obukhov Length (m)	L_{mod} is used here and it is just L from COARE (L_{COARE}) limited to >5	L_{mod} is used here and it is just L from COARE (L_{COARE}) limited to >5	L_{mod} is used here and it is just L from COARE (L_{COARE}) limited to >1	L_{mod} is used here and it is just L from COARE (L_{COARE}) limited to >5	L_{mod} is used here and it is just L from COARE (L_{COARE}) limited to >5
z0	Surface roughness Length(m)	Taken from COARE ouput	Taken from COARE ouput	Taken from COARE ouput	Taken from COARE ouput	Taken from COARE ouput
Bowen	Bowen Ratio	Ratio of the sensible heat flux from COARE to the latent heat flux from COARE, but limited to >0 and set to 0 if the sensible heat flux is <0	Ratio of the sensible heat flux from COARE to the latent heat flux from COARE, but limited to >0 and set to 0 if the sensible heat flux is <0	Ratio of the sensible heat flux from COARE to the latent heat flux from COARE, but limited to >0 and set to 0 if the sensible heat flux is <0	Ratio of the sensible heat flux from COARE to the latent heat flux from COARE, but limited to >0 and set to 0 if the sensible heat flux is <0	Ratio of the sensible heat flux from COARE to the latent heat flux from COARE, but limited to >0 and set to 0 if the sensible heat flux is <0
Albedo	Albedo	Set to 0.055 for all cases	Set to 0.055 for all cases	Set to 0.055 for all cases	Set to 0.055 for all cases	Set to 0.055 for all cases
Speed	Wind Speed (m/s)	From tracer experiment data	From tracer experiment data	From tracer experiment data	From tracer experiment data	From tracer experiment data
Dir	Wind Direction	Set to 270° for all cases and receptor always set on plume centerline	Set to 270° for all cases and receptor always set on plume centerline	Set to 270° for all cases and receptor always set on plume centerline	Set to 270° for all cases and receptor always set on plume centerline	Set to 270° for all cases and receptor always set on plume centerline
Zwind	Ref. Ht. for wind Speed (m)	Either 10m or 18m from tracer experiment data	Either 10m or 18m from tracer experiment data	Either 10m or 18m from tracer experiment data	Either 10m or 18m from tracer experiment data	Either 10m or 18m from tracer experiment data
temp	Temperature (°K)	From tracer experiment data	From tracer experiment data	From tracer experiment data	From tracer experiment data	From tracer experiment data
Ztemp	Ref. Ht. for Temperature (m)	Either 10m or 18m from tracer experiment data	Either 10m or 18m from tracer experiment data	Either 10m or 18m from tracer experiment data	Either 10m or 18m from tracer experiment data	Either 10m or 18m from tracer experiment data
prec code	Precip. Code (not used)	Always 9999	Always 9999	Always 9999	Always 9999	Always 9999
precip	Precipitation (not used)	-9.00 for all cases	-9.00 for all cases	-9.00 for all cases	-9.00 for all cases	-9.00 for all cases
RH	Relative Humidity (%)	From the tracer experiment data	From the tracer experiment data	From the tracer experiment data	From the tracer experiment data	From the tracer experiment data
pres	Barometric Pressure (mb)	Always 1000	Always 1000	Always 1000	Always 1000	Always 1000
CC	Cloud Cover (tenths)	Always 0	Always 0	Always 0	Always 0	Always 0

.pfl file

For 2 heights - Data for First Height

yr	year	81 or 82	81 or 82	81 or 82	81 or 82	81 or 82
mo	month	July or February	July or February	July or February	July or February	July or February
dy	day	Varies	Varies	Varies	Varies	Varies
hour	hour	Varies	Varies	Varies	Varies	Varies
height1	meas. Ht. (m)	10 all cases	10 all cases	10 all cases	10 all cases	10 all cases
last?	Indicator if more than one level is used	0 for first level	0 for first level	0 for first level	0 for first level	0 for first level
dir1	wind direction	The first half of the experimental data used 270 for all cases. The second have of the experimenal data used 999 for all cases	The first half of the experimental data used 270 for all cases. The second have of the experimenal data used 999 for all cases	The first half of the experimental data used 270 for all cases. The second have of the experimenal data used 999 for all cases	The first half of the experimental data used 270 for all cases. The second have of the experimenal data used 999 for all cases	The first half of the experimental data used 270 for all cases. The second have of the experimenal data used 999 for all cases
speed1	Wind Speed (m/s)	The first half of the hours used experimental data measured at this height	The first half of the hours used experimental data measured at this height	The first half of the hours used experimental data measured at this height	The first half of the hours used experimental data measured at this height	The first half of the hours used experimental data measured at this height

temp1	Temperature (°C)	6 of the 26 hours used experimental data measured at this height	6 of the 26 hours used experimental data measured at this height	6 of the 26 hours used experimental data measured at this height	6 of the 26 hours used experimental data measured at this height	6 of the 26 hours used experimental data measured at this height
SigTheta1	sigma theta (deg)	8 of the 26 hours used experimental data measured at this height	Assumed 999 for all horus	8 of the 26 hours used experimental data measured at this height	8 of the 26 hours used experimental data measured at this height	8 of the 26 hours used experimental data measured at this height
SigW1	Sigma W (m/s)	999 for all cases (not used)	999 for all cases (not used)	999 for all cases (not used)	999 for all cases (not used)	999 for all cases (not used)
For 2 heights - Data for Second Height						
yr	year	81 or 82	81 or 82	81 or 82	81 or 82	81 or 82
mo	month	July or February	July or February	July or February	July or February	July or February
dy	day	Varies	Varies	Varies	Varies	Varies
hour	hour	Varies	Varies	Varies	Varies	Varies
height2	meas. Ht. (m)	18 all cases	18 all cases	18 all cases	18 all cases	18 all cases
last?	Indicator if more than one level is used	1 for second level	1 for second level	1 for second level	1 for second level	1 for second level
dir2	wind direction	The first half of the experimental data used 999 for all cases. The second have of the experimenal data used 270 for all cases	The first half of the experimental data used 999 for all cases. The second have of the experimenal data used 270 for all cases	The first half of the experimental data used 999 for all cases. The second have of the experimenal data used 270 for all cases	The first half of the experimental data used 999 for all cases. The second have of the experimenal data used 270 for all cases	The first half of the experimental data used 999 for all cases. The second have of the experimenal data used 270 for all cases
speed2	Wind Speed (m/s)	The second half of the hours used experimental data measured at this height	The second half of the hours used experimental data measured at this height	The second half of the hours used experimental data measured at this height	The second half of the hours used experimental data measured at this height	The second half of the hours used experimental data measured at this height
temp2	Temperature (°C)	20 of the 26 hours used experimental data measured at this height	20 of the 26 hours used experimental data measured at this height	20 of the 26 hours used experimental data measured at this height	20 of the 26 hours used experimental data measured at this height	20 of the 26 hours used experimental data measured at this height
SigTheta2	sigma theta (deg)	13 of the 26 hours used experimental data measured at this height	Assumed 999 for all horus	13 of the 26 hours used experimental data measured at this height	13 of the 26 hours used experimental data measured at this height	13 of the 26 hours used experimental data measured at this height
SigW2	Sigma W (m/s)	999 for all cases (not used)	999 for all cases (not used)	999 for all cases (not used)	999 for all cases (not used)	999 for all cases (not used)

Pimso Beach Met. Data

Common Analysis for all Cases:

Input variables to COARE

Name	Description	Source or Value
	Latitude	35.1
	Longitude	-120.6
	Mix. Ht. For Gustiness Calc	-999 (dummy value, COARE uses 600m)
u(m/s)	Wind speed (m/s)	Tracer Experimental Data
tseaC	Temp. of Sea Surface (°C)	Tracer Experimental Data except when inconsistent with temperature gradient data, then calculated from temp. measurement height and temperature gradient
tairC	Air Temp. (°C)	Tracer Experimental Data
RH(%)	Relative Humidity (%)	Tracer Experimental Data
PresMb	Pressure (mb)	1000 for all hours (OCD default)
rsW/m2	Solar radiation (W/m^2)	0 for all hours
tsky	Sky cloud cover (tenths)	0 for all hours
Ceil(100ft)	Ceiling Height (100's ft)	888 for all hours
Rain(mm)	Rainfall (mm/h)	0 for all hours
hwaveM	Not used	not used -999 for all hours
twaveS	Not used	not used -999 for all hours
zws	Ht. of wind sensor (m)	20.5
ztemp	Ht. of temp. sensor (m)	7
zrh	Ht. of RH sensor (m)	7
ts_depth	Depth of sea surface meas. (m)	0.5

Output Variables from COARE

Symbol	Description	Units
hf	Sensible heat flux	W/m^2
ef	Latent heat flux	W/M^2
sst	Skin temperature (sst = tsea - dter + dsea)	Deg. C
tau	Wind stress	N/m^2
Wbar	Webb mean vertical velocity	m/s
rf	Relative humidity	%
dter	cool skin temperature difference	Deg C
dt_wrm	total warm layer temperature difference	Deg C

tk_pwp	thickness of warm layer	M
tkt*1000.	cool skin thickness	mm x 1000
Wg	gustiness factor	m/s
usr	M-O velocity scaling parameter u* = friction velocity	m/s
tsr	M-O temperature scaling parameter t*	Deg C
qsr*1000	M-O humidity scaling parameter q*	kg/kg
xmol	Obukov Length	M
zo	Velocity roughness length	M
zot	Temperature roughness length	M
zoq	Humidity roughness length	M

Analysis Specific to Cases:

		Case1	Case 2	Case 3	Case 4	Case 5
Name		aermod_venk	aermod_nosigma	aermod_5L	aermod	aermod_drax
.sfc file		pismo_venk.sfc	pismo_venk.sfc	pismo_5L.sfc	pismo.sfc	pismo_venk.sfc
.pfl file		pismo.pfl	pismo_nosigma.pfl	pismo.pfl	pismo.pfl	pismo.pfl
Sigma Θ		measured	predicted	measured	measured	measured
Obukhov		>5	>5	>1	>5	>5
Lateral Dispersion		aermod	aermod	aermod	aermod	draxler
Mix Hts.		Venketram >25	Venketram >25	Observed	Observed	Venketram >25

.SFC file:

yr	year	81 or 82	81 or 82	81 or 82	81 or 82	81 or 82
mo	month	December or June	December or June	December or June	December or June	December or June
dy	day	Varies	Varies	Varies	Varies	Varies
jday	Julian Day	Varies	Varies	Varies	Varies	Varies
hr	Hour	Varies	Varies	Varies	Varies	Varies
SHF	Sensible Heat Flux (W/m^2)	COARE Output Does not vary from Case to Case	COARE Output Does not vary from Case to Case	COARE Output Does not vary from Case to Case	COARE Output Does not vary from Case to Case	COARE Output Does not vary from Case to Case
ustar	surface friction velocity (m/s)	Ustar from COARE is multiplied by $(L_{mod}/L_{COARE})^{1/3}$ (see L disc. Below)	Ustar from COARE is multiplied by $(L_{mod}/L_{COARE})^{1/3}$ (see L disc. Below)	Ustar from COARE is multiplied by $(L_{mod}/L_{COARE})^{1/3}$ (see L disc. Below)	Ustar from COARE is multiplied by $(L_{mod}/L_{COARE})^{1/3}$ (see L disc. Below)	Ustar from COARE is multiplied by $(L_{mod}/L_{COARE})^{1/3}$ (see L disc. Below)
wstar	Convective velocity scale (m/s)	Not used for stable cases. If Unstable = $[(u^*)(Z_{i-conv})/(0.4L)]^{1/3}$ note u* is modified as above	Not used for stable cases. If Unstable = $[(u^*)(Z_{i-conv})/(0.4L)]^{1/3}$ note u* is modified as above	Not used for stable cases. If Unstable = $[(u^*)(Z_{i-conv})/(0.4L)]^{1/3}$ note u* is modified as above	Not used for stable cases. If Unstable = $[(u^*)(Z_{i-conv})/(0.4L)]^{1/3}$ note u* is modified as above	Not used for stable cases. If Unstable = $[(u^*)(Z_{i-conv})/(0.4L)]^{1/3}$ note u* is modified as above
VPTG	Vertical potential temperature gradient above PBL (°C/m)	Set = 0.01 for all cases	Set = 0.01 for all cases	Set = 0.01 for all cases	Set = 0.01 for all cases	Set = 0.01 for all cases
Zi (Conv)	Convective Mixing Height (m)	Not used for stable cases. If unstable use value from tracer study (source unknown).	Not used for stable cases. If unstable use value from tracer study (source unknown).	Not used for stable cases. If unstable use value from tracer study (source unknown).	Not used for stable cases. If unstable use value from tracer study (source unknown).	Not used for stable cases. If unstable use value from tracer study (source unknown).

Zi (mech)	Mechanical Mixing Height (m)	$2300(u^*)^{1.5}$ limited to at least 25 m note u* is modified as above	$2300(u^*)^{1.5}$ limited to at least 25 m note u* is modified as above	Used Experiment Reported values for $Z_{i\text{-}mech}$ (source unknown)	Used Experiment Reported values for $Z_{i\text{-}mech}$ (source unknown)	$2300(u^*)^{1.5}$ limited to at least 25 m note u* is modified as above
L	Monin-Obukhov Length (m)	L_{mod} is used here and it is just L from COARE (L_{COARE}) limited to >5 and <8888	L_{mod} is used here and it is just L from COARE (L_{COARE}) limited to >5 and <8888	L_{mod} is used here and it is just L from COARE (L_{COARE}) limited to >1 and <8888	L_{mod} is used here and it is just L from COARE (L_{COARE}) limited to >5 and <8888	L_{mod} is used here and it is just L from COARE (L_{COARE}) limited to >5 and <8888
z0	Surface roughness Length(m)	Taken from COARE ouput	Taken from COARE ouput	Taken from COARE ouput	Taken from COARE ouput	Taken from COARE ouput
Bowen	Bowen Ratio	Ratio of the sensible heat flux from COARE to the latent heat flux from COARE, but limited to >0 and set to 0 if the sensible heat flux is <0	Ratio of the sensible heat flux from COARE to the latent heat flux from COARE, but limited to >0 and set to 0 if the sensible heat flux is <0	Ratio of the sensible heat flux from COARE to the latent heat flux from COARE, but limited to >0 and set to 0 if the sensible heat flux is <0	Ratio of the sensible heat flux from COARE to the latent heat flux from COARE, but limited to >0 and set to 0 if the sensible heat flux is <0	Ratio of the sensible heat flux from COARE to the latent heat flux from COARE, but limited to >0 and set to 0 if the sensible heat flux is <0
Albedo	Albedo	Set to 0.055 for all cases	Set to 0.055 for all cases	Set to 0.055 for all cases	Set to 0.055 for all cases	Set to 0.055 for all cases
Speed	Wind Speed (m/s)	From tracer experiment data	From tracer experiment data	From tracer experiment data	From tracer experiment data	From tracer experiment data
Dir	Wind Direction	Set to 270° for all cases and receptor always set on plume centerline	Set to 270° for all cases and receptor always set on plume centerline	Set to 270° for all cases and receptor always set on plume centerline	Set to 270° for all cases and receptor always set on plume centerline	Set to 270° for all cases and receptor always set on plume centerline
Zwind	Ref. Ht. for wind Speed (m)	20.5 m for all cases	20.5 m for all cases	20.5 m for all cases	20.5 m for all cases	20.5 m for all cases
temp	Temperature (°K)	From tracer experiment data	From tracer experiment data	From tracer experiment data	From tracer experiment data	From tracer experiment data
Ztemp	Ref. Ht. for Temperature (m)	7 m for all cases	7 m for all cases	7 m for all cases	7 m for all cases	7 m for all cases
prec code	Precip. Code (not used)	Always 9999	Always 9999	Always 9999	Always 9999	Always 9999
precip	Precipitation (not used)	-9.00 for all cases	-9.00 for all cases	-9.00 for all cases	-9.00 for all cases	-9.00 for all cases
RH	Relative Humidity (%)	From the tracer experiment data	From the tracer experiment data	From the tracer experiment data	From the tracer experiment data	From the tracer experiment data
pres	Barometric Pressure (mb)	Always 1000	Always 1000	Always 1000	Always 1000	Always 1000
CC	Cloud Cover (tenths)	Always 0	Always 0	Always 0	Always 0	Always 0

.pfl file

For 2 heights - Data for First Height

yr	year	81 or 82	81 or 82	81 or 82	81 or 82	81 or 82
mo	month	December or June	December or June	December or June	December or June	December or June
dy	day	Varies	Varies	Varies	Varies	Varies
hour	hour	Varies	Varies	Varies	Varies	Varies
height1	meas. Ht. (m)	7 all cases	7 all cases	7 all cases	7 all cases	7 all cases
last?	Indicator if more than one level is used	0 for first level	0 for first level	0 for first level	0 for first level	0 for first level
dir1	wind direction	In all cases 999 (wind direction measured only at second hieght)	In all cases 999 (wind direction measured only at second hieght)	In all cases 999 (wind direction measured only at second hieght)	In all cases 999 (wind direction measured only at second hieght)	In all cases 999 (wind direction measured only at second hieght)
speed1	Wind Speed (m/s)	In all cases 99 (wind speed measured only at second hieght)	In all cases 99 (wind speed measured only at second hieght)	In all cases 99 (wind speed measured only at second hieght)	In all cases 99 (wind speed measured only at second hieght)	In all cases 99 (wind speed measured only at second hieght)
temp1	Temperature (°C)	Taken from tracer experimental data	Taken from tracer experimental data	Taken from tracer experimental data	Taken from tracer experimental data	Taken from tracer experimental data

SigTheta1	sigma theta (deg)	In all cases 999 (wind direction measured only at second hieght)	In all cases 999 (wind direction measured only at second hieght)	In all cases 999 (wind direction measured only at second hieght)	In all cases 999 (wind direction measured only at second hieght)	In all cases 999 (wind direction measured only at second hieght)
SigW1	Sigma W (m/s)	999 for all cases (not used)	999 for all cases (not used)	999 for all cases (not used)	999 for all cases (not used)	999 for all cases (not used)

For 2 heights - Data for Second Height

yr	year	81 or 82	81 or 82	81 or 82	81 or 82	81 or 82
mo	month	December or June	December or June	December or June	December or June	December or June
dy	day	Varies	Varies	Varies	Varies	Varies
hour	hour	Varies	Varies	Varies	Varies	Varies
height2	meas. Ht. (m)	20.5 all cases	20.5 all cases	20.5 all cases	20.5 all cases	20.5 all cases
last?	Indicator if more than one level is used	1 for second level	1 for second level	1 for second level	1 for second level	1 for second level
dir2	wind direction	270 for all cases	270 for all cases	270 for all cases	270 for all cases	270 for all cases
speed2	Wind Speed (m/s)	Taken from tracer experimental data	Taken from tracer experimental data	Taken from tracer experimental data	Taken from tracer experimental data	Taken from tracer experimental data
temp2	Temperature (°C)	99 for all cases (temp. not measured at this height)	99 for all cases (temp. not measured at this height)	99 for all cases (temp. not measured at this height)	99 for all cases (temp. not measured at this height)	99 for all cases (temp. not measured at this height)
SigTheta2	sigma theta (deg)	Taken from tracer experimental data	Taken from tracer experimental data	Taken from tracer experimental data	Taken from tracer experimental data	Taken from tracer experimental data
SigW2	Sigma W (m/s)	999 for all cases (not used)	999 for all cases (not used)	999 for all cases (not used)	999 for all cases (not used)	999 for all cases (not used)

Carpinteria Met. Data

Common Analysis for all Cases:

Input variables to COARE

Name	Description	Source or Value
	Latitude	34.4
	Longitude	-119.5
	Mix. Ht. For Gustiness Calc	-999 (dummy value, COARE uses 600m)
u(m/s)	Wind speed (m/s)	Tracer Experimental Data
tseaC	Temp. of Sea Surface (°C)	Tracer Experimental Data except when inconsistent with temperature gradient data, then calculated from temp. measurement height and temperature gradient
tairC	Air Temp. (°C)	Tracer Experimental Data
RH(%)	Relative Humidity (%)	Tracer Experimental Data
PresMb	Pressure (mb)	1000 for all hours (OCD default)
rsW/m2	Solar radiation (W/m^2)	0 for all hours
tsky	Sky cloud cover (tenths)	0 for all hours
Ceil(100ft)	Ceiling Height (100's ft)	888 for all hours
Rain(mm)	Rainfall (mm/h)	0 for all hours
hwaveM	Not used	not used -999 for all hours
twaveS	Not used	not used -999 for all hours
zws	Ht. of wind sensor (m)	Variable heights from 24 to 91 m depending on the experiment
ztemp	Ht. of temp. sensor (m)	9 m from tracer experiment data
zrh	Ht. of RH sensor (m)	9 m from tracer experiment data
ts_depth	Depth of sea surface meas. (m)	0.5 for all cases

Output Variables from COARE

Symbol	Description	Units
hf	Sensible heat flux	W/m^2
ef	Latent heat flux	W/M^2
sst	Skin temperature (sst = tsea - dter + dsea)	Deg. C
tau	Wind stress	N/m^2
Wbar	Webb mean vertical velocity	m/s
rf	Relative humidity	%
dter	cool skin temperature difference	Deg C

dt_wrm	total warm layer temperature difference	Deg C
tk_pwp	thickness of warm layer	M
tkt*1000.	cool skin thickness	mm x 1000
Wg	gustiness factor	m/s
usr	M-O velocity scaling parameter u* = friction velocity	m/s
tsr	M-O temperature scaling parameter t*	Deg C
qsr*1000	M-O humidity scaling parameter q*	kg/kg
xmol	Obukov Length	M
zo	Velocity roughness length	M
zot	Temperature roughness length	M
zoq	Humidity roughness length	M

Analysis Specific to Cases:

		Case1	Case 2	Case 3	Case 4	Case 5
Name		aermod_venk	aermod_nosigma	aermod	aermod_5L	aermod_drax
.sfc file		carp_venk.sfc	carp_venk.sfc	carp.sfc	carp_5L.sfc	carp_venk.sfc
.pfl file		carp.pfl	carp_nosigma.pfl	carp.pfl	carp.pfl	carp.pfl
Sigma Θ		measured	predicted	measured	measured	measured
Obukhov		>5	>5	>1	>5	>5
Lateral Dispersion		aermod	aermod	aermod	aermod	draxler
Mix Hts.		Venketram >25	Venketram >25	Observed	Observed	Venketram >25

.SFC file:

yr	year	85 in all cases	85 in all cases	85 in all cases	85 in all cases	85 in all cases
mo	month	September or October	September or October	September or October	September or October	September or October
dy	day	Varies	Varies	Varies	Varies	Varies
jday	Julian Day	Varies	Varies	Varies	Varies	Varies
hr	Hour	Varies	Varies	Varies	Varies	Varies
SHF	Sensible Heat Flux (W/m^2)	COARE Output Does not vary from Case to Case	COARE Output Does not vary from Case to Case	COARE Output Does not vary from Case to Case	COARE Output Does not vary from Case to Case	COARE Output Does not vary from Case to Case
ustar	surface friction velocity (m/s)	Ustar from COARE is multiplied by $(L_{mod}/L_{COARE})^{1/3}$ (see L disc. Below)	Ustar from COARE is multiplied by $(L_{mod}/L_{COARE})^{1/3}$ (see L disc. Below)	Ustar from COARE is multiplied by $(L_{mod}/L_{COARE})^{1/3}$ (see L disc. Below)	Ustar from COARE is multiplied by $(L_{mod}/L_{COARE})^{1/3}$ (see L disc. Below)	Ustar from COARE is multiplied by $(L_{mod}/L_{COARE})^{1/3}$ (see L disc. Below)
wstar	Convective velocity scale (m/s)	Not used for stable cases. If Unstable = $[(u^*)(Z_{i-conv})/(0.4L)]^{1/3}$ note u* is modified as above	Not used for stable cases. If Unstable = $[(u^*)(Z_{i-conv})/(0.4L)]^{1/3}$ note u* is modified as above	Not used for stable cases. If Unstable = $[(u^*)(Z_{i-conv})/(0.4L)]^{1/3}$ note u* is modified as above	Not used for stable cases. If Unstable = $[(u^*)(Z_{i-conv})/(0.4L)]^{1/3}$ note u* is modified as above	Not used for stable cases. If Unstable = $[(u^*)(Z_{i-conv})/(0.4L)]^{1/3}$ note u* is modified as above
VPTG	Vertical potential temperature gradient above PBL (°C/m)	Set = 0.01 for all cases	Set = 0.01 for all cases	Set = 0.01 for all cases	Set = 0.01 for all cases	Set = 0.01 for all cases
Zi (Conv)	Convective Mixing Height (m)	Not used for stable cases. If unstable use value from tracer study (source unknown).	Not used for stable cases. If unstable use value from tracer study (source unknown).	Not used for stable cases. If unstable use value from tracer study (source unknown).	Not used for stable cases. If unstable use value from tracer study (source unknown).	Not used for stable cases. If unstable use value from tracer study (source unknown).

Zi (mech)	Mechanical Mixing Height (m)	$2300(u^*)^{1.5}$ limited to at least 25 m note u* is modified as above	$2300(u^*)^{1.5}$ limited to at least 25 m note u* is modified as above	Used Experiment Reported values for $Z_{i\text{-mech}}$ (source unknown)	Used Experiment Reported values for $Z_{i\text{-mech}}$ (source unknown)	$2300(u^*)^{1.5}$ limited to at least 25 m note u* is modified as above
L	Monin-Obukhov Length (m)	L_{mod} is used here and it is just L from COARE (L_{COARE}) limited to >5	L_{mod} is used here and it is just L from COARE (L_{COARE}) limited to >5	L_{mod} is used here and it is just L from COARE (L_{COARE}) limited to >1	L_{mod} is used here and it is just L from COARE (L_{COARE}) limited to >5	L_{mod} is used here and it is just L from COARE (L_{COARE}) limited to >5
z0	Surface roughness Length(m)	Taken from COARE ouput	Taken from COARE ouput	Taken from COARE ouput	Taken from COARE ouput	Taken from COARE ouput
Bowen	Bowen Ratio	Ratio of the sensible heat flux from COARE to the latent heat flux from COARE, but limited to >0 and set to 0 if the sensible heat flux is <0	Ratio of the sensible heat flux from COARE to the latent heat flux from COARE, but limited to >0 and set to 0 if the sensible heat flux is <0	Ratio of the sensible heat flux from COARE to the latent heat flux from COARE, but limited to >0 and set to 0 if the sensible heat flux is <0	Ratio of the sensible heat flux from COARE to the latent heat flux from COARE, but limited to >0 and set to 0 if the sensible heat flux is <0	Ratio of the sensible heat flux from COARE to the latent heat flux from COARE, but limited to >0 and set to 0 if the sensible heat flux is <0
Albedo	Albedo	Set to 0.055 for all cases	Set to 0.055 for all cases	Set to 0.055 for all cases	Set to 0.055 for all cases	Set to 0.055 for all cases
Speed	Wind Speed (m/s)	From tracer experiment data (limited to >1)	From tracer experiment data (limited to >1)	From tracer experiment data (limited to >1)	From tracer experiment data (limited to >1)	From tracer experiment data (limited to >1)
Dir	Wind Direction	Taken from tracer experimental data. Peak Model prediction from all receptors compared to observed value	Taken from tracer experimental data. Peak Model prediction from all receptors compared to observed value	Taken from tracer experimental data. Peak Model prediction from all receptors compared to observed value	Taken from tracer experimental data. Peak Model prediction from all receptors compared to observed value	Taken from tracer experimental data. Peak Model prediction from all receptors compared to observed value
Zwind	Ref. Ht. for wind Speed (m)	Variable heights from 24 to 91 m depending on the experiment	Variable heights from 24 to 91 m depending on the experiment	Variable heights from 24 to 91 m depending on the experiment	Variable heights from 24 to 91 m depending on the experiment	Variable heights from 24 to 91 m depending on the experiment
temp	Temperature (°K)	From tracer experiment data	From tracer experiment data	From tracer experiment data	From tracer experiment data	From tracer experiment data
Ztemp	Ref. Ht. for Temperature (m)	9 m for all cases	9 m for all cases	9 m for all cases	9 m for all cases	9 m for all cases
prec code	Precip. Code (not used)	Always 9999	Always 9999	Always 9999	Always 9999	Always 9999
precip	Precipitation (not used)	-9.00 for all cases	-9.00 for all cases	-9.00 for all cases	-9.00 for all cases	-9.00 for all cases
RH	Relative Humidity (%)	From the tracer experiment data	From the tracer experiment data	From the tracer experiment data	From the tracer experiment data	From the tracer experiment data
pres	Barometric Pressure (mb)	Always 1000	Always 1000	Always 1000	Always 1000	Always 1000
CC	Cloud Cover (tenths)	Always 0	Always 0	Always 0	Always 0	Always 0

.pfl file

For 2 heights - Data for First Height

yr	year	85 in all cases	85 in all cases	85 in all cases	85 in all cases	85 in all cases
mo	month	September or October	September or October	September or October	September or October	September or October
dy	day	Varies	Varies	Varies	Varies	Varies
hour	hour	Varies	Varies	Varies	Varies	Varies
height1	meas. Ht. (m)	9 in all cases	9 in all cases	9 in all cases	9 in all cases	9 in all cases
last?	Indicator if more than one level is used	0 for first level	0 for first level	0 for first level	0 for first level	0 for first level
dir1	wind direction	In all cases 999 (wind direction measured only at second hieght)	In all cases 999 (wind direction measured only at second hieght)	In all cases 999 (wind direction measured only at second hieght)	In all cases 999 (wind direction measured only at second hieght)	In all cases 999 (wind direction measured only at second hieght)
speed1	Wind Speed (m/s)	In all cases 99 (wind speed measured only at second hieght)	In all cases 99 (wind speed measured only at second hieght)	In all cases 99 (wind speed measured only at second hieght)	In all cases 99 (wind speed measured only at second hieght)	In all cases 99 (wind speed measured only at second hieght)
temp1	Temperature (°C)	Taken from tracer experimental data	Taken from tracer experimental data	Taken from tracer experimental data	Taken from tracer experimental data	Taken from tracer experimental data

SigTheta1	sigma theta (deg)	In all cases 999 (wind direction measured only at second hieght)	In all cases 999 (wind direction measured only at second hieght)	In all cases 999 (wind direction measured only at second hieght)	In all cases 999 (wind direction measured only at second hieght)	In all cases 999 (wind direction measured only at second hieght)
SigW1	Sigma W (m/s)	999 for all cases (not used)	999 for all cases (not used)	999 for all cases (not used)	999 for all cases (not used)	999 for all cases (not used)
For 2 heights - Data for Second Height						
yr	year	85 in all cases	85 in all cases	85 in all cases	85 in all cases	85 in all cases
mo	month	September or October	September or October	September or October	September or October	September or October
dy	day	Varies	Varies	Varies	Varies	Varies
hour	hour	Varies	Varies	Varies	Varies	Varies
height2	meas. Ht. (m)	From Tracer Experimental Data. Varies by hour from 24m - 91 m	From Tracer Experimental Data. Varies by hour from 24m - 91 m	From Tracer Experimental Data. Varies by hour from 24m - 91 m	From Tracer Experimental Data. Varies by hour from 24m - 91 m	From Tracer Experimental Data. Varies by hour from 24m - 91 m
last?	Indicator if more than one level is used	1 for second level	1 for second level	1 for second level	1 for second level	1 for second level
dir2	wind direction	Taken from tracer experimental data. Peak Model prediction from all receptors compared to observed value	Taken from tracer experimental data. Peak Model prediction from all receptors compared to observed value	Taken from tracer experimental data. Peak Model prediction from all receptors compared to observed value	Taken from tracer experimental data. Peak Model prediction from all receptors compared to observed value	Taken from tracer experimental data. Peak Model prediction from all receptors compared to observed value
speed2	Wind Speed (m/s)	Taken from tracer experimental data	Taken from tracer experimental data	Taken from tracer experimental data	Taken from tracer experimental data	Taken from tracer experimental data
temp2	Temperature (°C)	99 for all cases (temp. not measured at this height)	99 for all cases (temp. not measured at this height)	99 for all cases (temp. not measured at this height)	99 for all cases (temp. not measured at this height)	99 for all cases (temp. not measured at this height)
SigTheta2	sigma theta (deg)	Taken from tracer experimental data	Taken from tracer experimental data	Taken from tracer experimental data	Taken from tracer experimental data	Taken from tracer experimental data
SigW2	Sigma W (m/s)	999 for all cases (not used)	999 for all cases (not used)	999 for all cases (not used)	999 for all cases (not used)	999 for all cases (not used)