Responses to Information and Data Request Number 2 from Herman Wong to Shell

B. Clarification to Shell's Response to First Information and Data Request dated 14 February 2011.

1. *There is still doubt about the quality of the peer-review for the Gryning and Batchvarova paper. The journal, International Journal of Environment and Pollution, was unknown to us until now. Neither EPA nor the University of Washington has subscriptions to the journal. The journal has a low impact factor and a couple of highly - respected academic researchers in pollutant dispersion we surveyed had never heard of this journal and were equally skeptical of its peer-review quality. Please provide substantive and convincing information about this journal's ability to provide a high standard of peer review.*

Response: As was noted, the article referenced in the comment was published in the *International Journal of Environment and Pollution* [Gryning, Sven-Erik and Ekaterina Batchvarova, 2003: Marine atmospheric boundary-layer height estimated from NWP model output. *International Journal of Environment and Pollution*, **20**, 147-153]. Submitted papers in this journal are refereed through a double blind process. We would thus advocate that the materials in the *Journal* have a good "impact factor".

Notwithstanding our confidence in the *Journal, w*e would suggest that EPA place more weight on evaluating the reputation and standing of the particular authors of the paper than generalizing a review based on the publication in which it appears. Gryning and Batchvarova are recognized world experts on numerical techniques for the estimation of the mixed layer heights in marine and coastal environments and have chaired conferences on this topic, contributed chapters in several books and published in *Boundary Layer-Meteorology*, *Quarterly Journal of The Royal Meteorological Society*, and *Atmospheric Environment* among others .[1] [2] Thus, Shell would reiterate the qualifications of the submitted authors as well.

2. *In order to accept this modeling methodology, we need a description of how all meteorological variables are prepared. The "mechanical description" is important information we need to have as soon as possible, especially as it relates to the empirical relationships for the mixing height and the vertical potential temperature gradient.*

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[1] Example: **Length Scales of the Neutral Wind Profile over Homogeneous Terrain** Pena Diaz, Alfredo ; Gryning, Sven-Erik ; Mann, Jakob ; Hasager, Charlotte Bay in journal: Journal of Applied Meteorology and Climatology (ISSN: 1558-8424) (DOI: 10.1175/2009JAMC2148.1) , vol: 49, issue: 4, pages: 792-806, 2010, American Meteorological Society.

[2] Example: **On the extension of the wind profile over homogeneous terrain beyond the surface boundary layer** Gryning, Sven-Erik ; Batchvarova, Ekaterina ; Brümmer, B. ; Jørgensen, H.E. ; Larsen, Søren Ejling in journal: Boundary-Layer Meteorol. (ISSN:) (DOI: 10.1007/s10546-007-9166-9) , vol: 124, pages: 251-268, 2007

Response. The" mechanical description" has been provided as Attachment A to this response document. Mechanical descriptions for the procedures used in the COARE-AERMOD evaluation study were also include in the "README.txt" files and User's Guide contained on the CD delivered to Region 10 on March 9, 2011:

C. Second Information/Data Request

The following information and data request are based on R10's review of the "Evaluation of COARE-AERMOD Alternative Modeling Approach Support for Simulation of Shell Exploratory Drilling Sources in the Beaufort and Chukchi Seas" dated December 2010.

1. *On page 1, reference is made to Section 3.2.2.d.iv in the Appendix W of 40 CFR 51. This subsection is not found in Appendix W. Please clarify.*

Response: The referenced section of the Guideline is in error. The correct reference should have been 3.3.3.e.iv not as stated in the December report.

2. *On page 2, fourth bullet, "24-hour" should appear for clarity between "new" and "PM2.5 ".*

Response: The requested change will be made.

3. *The fifth bullet on page 3 states that shoreline fumigation is not critical because the model highest concentration impacts should occur at offshore locations. However, a cumulative impact analysis may be requested with receptor points located at both over water and terrestrial locations. What provisions has Shell made should R10 make this request as part of an ambient air quality impact analysis?*

Response: Shell has presently made no provisions for this analysis within the COARE-AERMOD approach. However, it should be noted that the distance between the drilling locations and the shore where potential fumigation could occur is over 50 kilometers for all locations in the Chukchi Sea and for the Beaufort Sea, the locations are still on the order of many kilometers from any of the villages. The AERMOD model has no provision for fumigation calculations. Further AERMOD has no provision for the internal boundary and subsequent changes in mixing that might occur due to changes in land use for terrestrial applications. Given the long distances to the villages, it seems appropriate that the CALPUFF model should be used in the event EPA requests that this issue be addressed. The CALPUFF model does contain an algorithm for addressing fumigation or spatial changes in terrain, land use or meteorology in general. Another factor to be considered is that the real purpose of fumigation analyses is to treat cases where very elevated plumes are mixed rapidly to the ground when passing over a change in surface regime (i.e.; from stable to unstable boundary layers). The classic fumigation case is a power plant located on a coastline. For exploratory drilling sources, however, not only are the sources located far from the shoreline, but also, the plumes from Shell's sources are relatively low and would be expected to have reached the surface by the time they reach the shore.

4. *In Section 4.1 on page 5, three over water tracer gas experiments (i.e., Pismo, Beach, CA; Cameron, LA and Carpinteria, CA) are listed, described and used in the evaluation to satisfy Condition iv in Section 3.2.2.e of Appendix W. For the evaluations of OCD and/or CALPUFF,*

tracer gas experiments from Ventura, CA and Oresund, Denmark/Sweden were also used. Please explain why these two experiments were not used in the evaluation of COARE.

Response. 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.

5. *In the paragraph on the bottom of page 5 and carried over to page 6, it is states "...we adjusted the air-sea temperature difference to be at least as stable as indicated by the virtual temperature lapse rate" for Pismo Beach. Furthermore, the third bullet on page 8, implies that "...the air-sea temperature difference was based on the lapse rate applied from the surface to the temperature measurement height." We assume that this approach was also used in Cameron meteorological data. Please provide a sample calculation.*

Response: An example would be for the Cameron, LA experiment, hour 16 of February 15, 1982. For this hour the air-sea temperature difference (Ta-Ts) was listed in the experimental data as 0 °C. However, when this experiment was originally used to evaluate the OCD model, it used a potential temperature gradient of 0.06 °C/m. Since this is a very stable case, the air-sea temperature difference was reset to the difference between the air temperature at the measurement height (for this hour, 10 meters) and a calculated air temperature at the sea surface using the potential temperature gradient and the lapse rate. Since this calculation is done in a spreadsheet, it looks like this:

```
IF(S??>0,MAX((S??+lapse)*C??,M??),M??)
```

Where: ?? varies from hour to hour as each hour occupies a separate row in the spreadsheet. Since in the current example (hour 16 of 2/12/82), the row number is 11, the formula is:

IF(S11>0,MAX((S11+lapse)*C11,M11),M11)

In this example, S11 is the potential temperature gradient of 0.06 °C/m, lapse is the dry adiabatic lapse rate of -0.0098 °C/m, C11 is the height of the temperature sensor of 10 meters and M11 is the experiment reported air-sea temperature difference of 0 °C. So the formula first checks to see if this is a stable case by testing S11 to see if it is greater than 0. If not then the air sea temperature difference from the experiment (M11) is used unchanged. If it is stable (as this hour was), the experiment-reported air-sea temperature difference is compared with a calculated value and the higher of the two values used. The calculated value is the height of the temperature measurement (C11) times the sum of the potential temperature gradient and the dry adiabatic lapse rate. A sample calculation of this latter factor is:

(S11 + lapse)*C11

$$(0.06 - 0.0098)(10) = 0.502$$

Since 0.502 °C is greater than 0 °C, the value of 0.502 °C is used for the air-sea temperature difference.

6. *In the first bullet on Section 4.2.1, page 8, Shell states that COARE is insensitive to certain meteorological variables in the Arctic. If Shell is making a recommendation with respect to input data, please explain.*

Response: Shell is not making a recommendation for all potential applications of the method. We simply stated our observations based on sensitivity tests with Arctic meteorology and note that the authors of the CALPUFF evaluations had the same recommendation for their model evaluation studies using the Carpinteria, Cameron and Pismo Beach data sets. The purpose of this sentence is simply to explain why certain options within the COARE algorithm were not used in the model evaluation. The application of the COARE approach should be case-by-case decisions based on the data available and the setting.

7. *Please clarify the sentence on page 10, second bullet that states "Plume rise is not applicable and these conditions do not occur in the current evaluation."*

Response: Shell agrees that plume rise and plume penetration are important to proper characterization of air pollutant dispersion. Here we meant plume rise and plume penetration are not important to these specific tracer studies. The tracer experiments being used in the evaluations of the COARE-AERMOD approach were releases of tracer gas from ships or platforms. The tracer gases were released at ambient conditions without appreciable momentum, thus neither momentum plume rise nor thermal plume rise was a factor in the experimental data.

8. *On page 10, first full paragraph, last two sentences, it states that a minimum mechanical mixing height is set at 25-m and the corresponding u* is 0.05 m/sec to avoid numerical problems. This 25-m height was employed in evaluation Case 1, Case 2, and Case 5 as detailed on page 11. However, evaluation Case 3 and Case 4 did not utilize a minimum height. We believe there is insufficient technical justification in the record to support a minimum mechanical mixing height.*

a. Please provide qualitative and quantitative technical justifications for the use of a 25-m minimum mechanical mixing height.

Response: Reasonable application of the dispersion algorithms with AERMOD in many instances require that the variables used in the various equations are limited in range. Wind speed is not allowed to less than the threshold of the anemometer, the absolute value of the Monin-Obukhov length must be greater than 1 m (we recommend 5 m in our evaluation), the vertical potential lapse rate must be greater than 0.005 C/m, and there are minimum allowed turbulent velocities for sigma-w and sigma-v. Mixing heights predicted using the friction velocity can be very small over water because the surface roughness length is very small. We believe it is also prudent to set a minimum for the mixed layer height and believe 25 m is a reasonable lower limit.

There are both numerical and practical reasons for our selection. A minimum mixing height must be used with the AERMOD model since the variable is used in the denominator of several equations. For example for the horizontal dispersions parameter σ_y:

$$\sigma_y = (\sigma_v x)/\{u[1 + 78(0.46/\max(z,0.46))((\sigma_v x)/(u z_i))^{0.3}]\}$$

where Z_i is the mixing height, z is the height of the plume, x is the downwind distance, σ_v is standard deviation of the crosswind velocity, and u the wind velocity. Note that the equation and previous code protects against $u=0$ and $z=0$, but not a mixing height (Z_i) of zero.

We also recommend that an equation should not be used outside of the range of the data used in its development and believe that some lower limit must be specified. The above equation and the equation used by AERMOD for the vertical dispersion from sources near the surface differ from simpler expressions used by CALPUFF, OCD and many other models, because the authors cited poor performance for the Prairie Grass field experiment. The equation above is an empirical fit to the Prairie Grass data set and should be applied with caution when the variables are well outside those used for the fit. The Prairie Grass field study is the sole experiment (out of 17) that examined dispersion from a near surface release. In the other datasets used in the AERMOD model evaluation study, plumes were influenced by downwash or were sufficiently high that the surface dispersion algorithms in AERMOD are not that important. The minimum mixing height used in the Prairie Grass experiment simulations was 67 m based on the input files from EPA's website.[3] We believe mixing heights 0.01, 0.1, 1, or even 10 m are well outside the range used to develop the near surface dispersion algorithms in AERMOD and 25 m is a reasonable lower limit. The lower limit should be imposed in the AERMOD code, but we have imposed the limit in the input data so the "default" AERMOD could be used without modification.

We also cite as further justification of a minimum mixing height the default of 50 m used by CALPUFF and note that the minimum mixing height in the OCD and CALPUFF overwater model evaluations were all 50 m. We believe 25 m is a reasonable lower limit for overwater applications of AERMOD using

[3] The Prairie Grass AERMOD files can be found at http://www.epa.gov/ttn/scram/7thconf/aermod/pgrass.zip. The meteorological file used is "PGRSURF.222".

precedent from the OCD/CALPUFF field studies, the minimum value used in the Prairie Grass simulations, and our own evaluations with COARE-AERMOD.

b. *Besides Case 3 and Case 4, please identify and discuss any other cases in which observed mechanical mixing heights could be used without a minimum mechanical mixing height, and the results and statistics would improve.*

Response: At the request of EPA, an additional sensitivity analysis was conducted for Case 1 in the event different, or no restrictions were placed on the mechanical mixing heights. The results of this analysis have been reported in Attachment B to this response document. The results of this sensitivity analysis show that performance of the COARE-AERMOD approach decreases with lower or no limit on the mixing height. For low or middle level concentrations, there is little to no difference between the assumptions on mixing height, but the very highest concentrations in the distribution are those with low mixing heights. With no limits on the mixing height, very high concentrations are computed by AERMOD, that are not seen in the measured data. Accordingly, Shell feels for the purposes of this model evaluation, it is necessary to impose some limit on this parameter.

c. *Please identify and discuss any other mechanical height options for use in Cases 1, 3, and 5. One possibility is 10 meters, the lowest resolvable height of the Kipp & Zonen MTP 5-P temperature profiler at Endeavor Island.*

Response: As discussed under (a) above, there are many potential values that could be used, including 50 meters. For the purposes of this model evaluation exercise, the value of 25 meters was chosen to be somewhat more conservative than the 50 m used in the previous CALPUFF/OCD model evaluations performed with these same data sets. The resolvable heights from the profiler on Endeavor Island are not relevant to the experiments in Louisiana and California.

d. *If we believe a different minimum mechanical mixing height or no minimum height is more appropriate and defensible based on your responses, we may request Shell to generate the applicable evaluation cases including the use of those listed on page 11, if appropriate.*

Response: Comment noted.

e. *Please provide a frequency distribution of available measured representative mechanical mixing height data focusing on the lowest 10-m and 25-m.*

Response: In subsequent conversations with EPA clarification has been provided that EPA is seeking a mixing height frequency distribution for the profile data collected at Endeavor Island. These data are not relevant to the experiments in Louisiana or California, but may be important in future applications of the COARE-AERMOD application. Measured mixing heights have been extracted from the actual temperature profiles taken by the profiler at Endeavor Island. The following table is a frequency distribution of these measured data collected in 2010:

Frequency Distribution of Endeavor Island Measured Mixing Heights		
(A) Mixing Height	Number of Hours Equal or	Percentage of Hours Equal or

(m)	Less than Column (A)	Less than Column (A)
10	24	1%
20	79	5%
20	79	2%
30	151	10%
40	284	20%
50	430	30%
80	702	50%
100	837	60%
150	1011	70%
200	1135	80%
250	1265	90%
300	1324	95%
400	1366	98%
650	1383	99%
700	1392	100%

f. Please provide a frequency distribution of available predicted mechanical mixing height data focusing on the lowest 10-m and 25-m.

Response: In subsequent conversations with EPA clarification has been provided that EPA is seeking a mixing height frequency distribution for the predicted mixing heights using the empirical relationship developed by Bart Brashers for calculating mixing height at the two locations in the Arctic, when actual mixing height data are not available. Specifically, this refers to the mixing height data computed for the Beaufort Sea in 2009 and the Chukchi Sea for 2009 and 2010. These data are not relevant to the experiments in Louisiana or California, but may be important in future applications of the COARE-AERMOD application. The following table is a frequency distribution of these predicted mixing heights for the three cases (Beaufort 2009, Chukchi 2009, and Chukchi 2010) specified above:

Frequency Distribution of Predicted Mixing Heights for Beaufort and Chukchi Sea Modeling Studies		
(A) Mixing Height (m)	Number of Hours Equal or Less than Column (A)	Percentage of Hours Equal or Less than Column (A)
23	53	1%
27	108	2%
36	276	5%
46	518	10%
68	1061	20%
91	1590	30%
137	2661	50%
163	3181	60%
192	3703	70%
228	4234	80%
288	4774	90%
376	5038	95%

585	5197	98%
775	5250	99%
1526	5304	100%

g. Please confirm that there is no minimum convective mixing height.

Response: The convective mixing heights in the model evaluation study were not limited in any fashion. "Observed" mixing heights were used for the convective estimates in the COARE-AERMOD simulations. Note however no "observed" mixing heights in any of the field studies were less than 50 m.

9. On page 10, fourth bullet, six variables are listed but not used in the evaluation simulations. Please explain the relevance for this listing.

Response: The variables are listed for completeness of the record explaining why these variables appear in the model files. AERMOD reads these variables each hour and they must be present or the model will not run.

10. On page 11, first paragraph, explain the differences in the five cases with respect to the measured and calculated meteorological variable used to generate surface file and profile file.

Response: Attachment A provides details on how the meteorological variables used by AERMOD are calculated from the input meteorological data for the four Arctic scenarios (i.e.; Beaufort 2009, Beaufort 2010, Chukchi 2009, Chukchi 2010). In the disk that was provided to EPA on March 8, a number of Excel spreadsheets were provided. For example, for Cameron, there is a directory called Cameron\met that contains a spreadsheet entitled "Cameron-AERMOD_prep_met.xlsx" which has all the information on how the meteorological files (.sfc and .pfl) were created for the AERMOD runs. The worksheet within that spreadsheet entitled "sfc" has the .sfc for Case 1. The worksheet entitled "pfl" has the .pfl file for Case 1. Case 2 for Cameron comes from the same spreadsheet. The surface file is the same, but the .pfl file comes from the worksheet entitled "pflnosig" in the same spreadsheet. Case 3 for Cameron is the same as Case 1, and comes from the same worksheet as Case 1, but before exporting the data in the spreadsheet to the .sfc file, the values on the "params" worksheet for lcrit and venk were set to "1.0" and "FALSE", respectively. Similar to Case 3, Case 4 is taken from the same worksheets as Case 1, except that the value of lcrit on the params worksheet is maintained at 5 although the parameter venk is changed to "FALSE as was done for Case 3. Finally, Case 5 was performed with exactly the same input values as Case 1. The differences between Case 1 and Case 5 relate to a change that was made to AERMOD itself as described on page 11 of the document. Cases 1-4 used AERMOD exactly as it comes from the EPA website, but to impose the conditions of Case 5, AERMOD itself was modified. By examining these spreadsheets for Cameron, Pismo and Carpinteria, EPA can see exactly how all the meteorological variables were computed.

11. On page 15, third bullet,

a. Since it always better to use site specific or representative meteorological data, please explain in further detail the sentence "An estimate of the mechanical mixing *height based on the friction velocity, as in AERMET, was a better alternative than using the observed mixing height from the field studies."*

Response: The mixing height data in these tracer studies were not well documented, so the source of the data used in the field studies is unclear. We agree a good measurement for mixing heights would be preferable to an estimate, but noted that some of the data used in the field experiments did not appear to reconcile with other measurements. For example a constant mixing height of 500m was used for all hours in the Carpinteria data set. This does not appear to be consistent with the very light winds and stable conditions reported. We note that at the time these tracer studies ISC was the regulatory default dispersion model, and that ISC is not sensitive to mixing height the way AERMOD is. So there was little motivation for the researchers at the time to measure the mixing height with any precision.

b. The predicted mixing height was compared to the mixing height from what station?

Response: We simply note estimates for mixing heights appear to result in better model performance in some instances than the "observation" reported in the field study. We did not attempt to resurrect the measurement databases from the original field studies from 30 years ago. We did not compare predicted mixing heights to measurements in this study.

c. Please provide the equation referred to in the last sentence.

Response: We mean the replacement equation on page 11 of the evaluation study for the horizontal dispersion parameter σ_y that does not depend on the mixing height.

12. Please confirm that Case 1 in the December 2010 evaluation document has been selected by Shell and will be used in its over water modeling analysis.

Response: No, the cases were unique to the model evaluation study. The actual simulations in the Arctic are different because the profiler data are available and have been used to compute mixing heights. The Cases in the model performance study provide insight in the sensitivities of the approach to some of the variable ways the data can be assembled. The model evaluation shows the COARE-AERMOD, or AERMOD simulations in general, can be sensitive to the mixing height. The actual method employed to provide mixing heights should be based on the data available and meteorological conditions. We believe the Endeavor Island profiler provides the best means to estimate mixing heights for Shell sources in the Arctic.

13. Please provide a CD containing the evaluation files including all input and output files, spreadsheets, code...etc.

Response: A CD has been provided to EPA on March 9, 2011 with the requested information.

14. Shell has completed an alternative model demonstration under Section 3.2.2.e in Appendix W of 40 CFR 51 and intends to use the model in its project specific ambient air quality impact analysis. R10 will public notice of the use of the model as well as make the all relevant materials available to the public for review and comment. To facilitate public understanding, Shell is requested to provide a glossary of terms that includes at a minimum, the below *technical terms and/or acronyms. It is suggested that the glossary include a write definition in layman terms followed by a formula, if appropriate.*

The terms and/or acronyms include:

Absolute humidity
Bulk Richardson number
COARE bulk air-sea flux
Convective mixing height
Convective velocity scale
Cool skin
Critical Richardson number
Dew point
Empirical relationships
Friction velocity or u%
Marine boundary layer
Monin-Obukhov length
Relative humidity
Sea surface temperature
Shoreline fumigation
Similarity theory
Skin temperature
Stable boundary layer height
Stable mixing height
Surface energy fluxes
Surface Rossby number
Surface roughness length
Vertical potential temperature gradient
Virtual potential lapse temperature
Virtual temperature
Warm layer
Well-developed or deep sea
Wet bulb temperature

Response: A glossary of terms has been prepared and is provided as Attachment C. It should be noted that there are a variety of definitions for many of the terms requested. We have attempted to provide a general definition and in some cases a definition specific to the COARE-AERMOD application. We welcome EPA's input if they feel alternative additional or alternative definitions are appropriate. The glossary can be viewed as a living document that may change over time as additional terms or further clarification is needed.

Attachment A

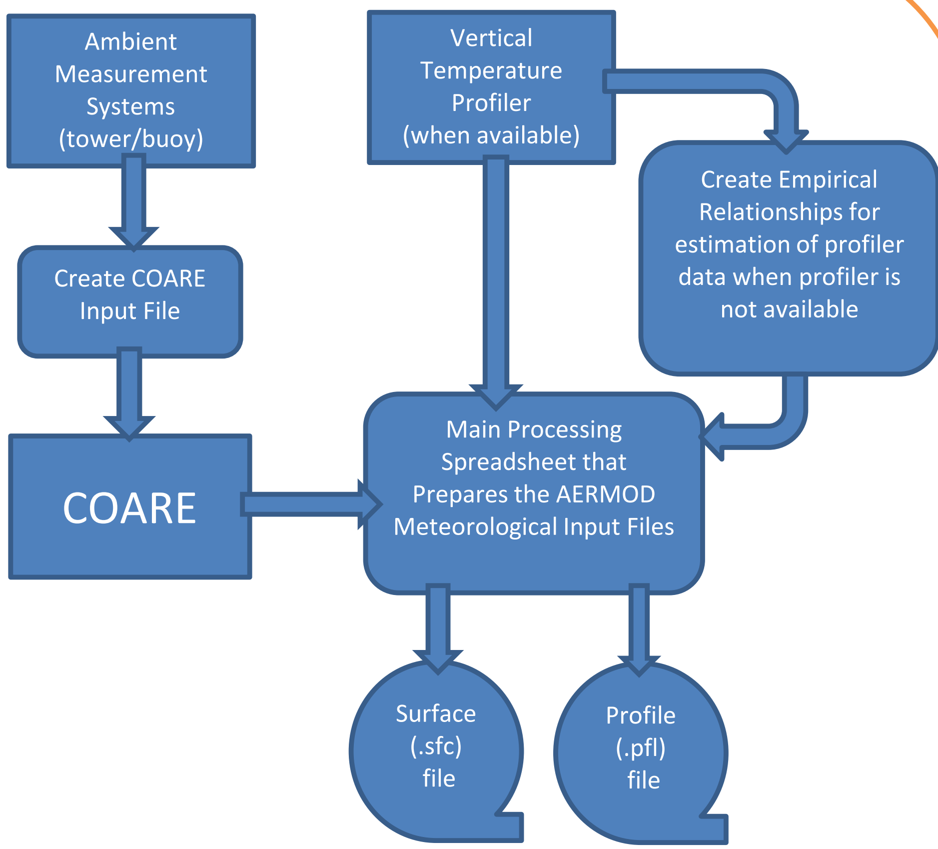
Detailed Description of Meteorological Data Set Preparation Process

Determination of AERMOD Meteorological Parameters for Shell Offshore Drilling Program Modeling, using the COARE algorithm as a substitute for AERMET

For the Shell Outer Continental Shelf (OCS) proposed oil exploration program air quality modeling analyses have been required to obtain air quality permits. The model currently proposed is the EPA's current guideline model, AERMOD. While AERMOD is appropriate for over-land conditions and can be used for ice-cover conditions that occur for much of the year in the Arctic, for periods of open water, the standard method of preparing meteorological data for AERMOD using the AERMET pre-processor, is not appropriate. Shell has proposed the use of an alternate method for preparation of meteorological data for open water conditions based on the well know COARE algorithm. This approach, frequently called the COARE-AERMOD approach, has been extensively discussed with EPA in previous meetings and documents. The purpose of this document is to provide a more "mechanical" explanation of the steps taken in this approach for processing the meteorological data. The following steps indicate the process:

- Step 1. Collect and assemble raw meteorological data. The sources of data include surface monitoring stations, buoy meteorological collection stations, and a vertical temperature profiler system located on Endeavor Island.
- Step 2. Prepare inputs for the COARE program. The COARE program is a FORTRAN program written to compute heat fluxes and other meteorological parameters from some of the measured data.
- Step 3. Run the COARE program
- Step 4. Process the profiler data to determine mixing heights and potential temperature gradients based on measured temperature profiles.
- Step 5. Development of a statistical relationship between the processed mixing heights and other meteorological parameters, so that mixing heights can be inferred from the other meteorological parameters for periods when the profiler data are not available.
- Step 6. Import the COARE program results and the mixing height data into an Excel spreadsheet that in turn is used to calculate the actual meteorological parameters required by AERMOD.
- Step 7. Export the meteorological data from the spreadsheet in the format needed by AERMOD.

The following flowchart depicts the process of using COARE to produce the two meteorological files needed by AERMOD (the surface file .sfc and the profile file .pfl). Ambient meteorological stations, such as Reindeer Island, the Buoy's or Deadhorse, provide raw meteorological parameters needed by COARE. COARE in turn calculates heat fluxes and other meteorological parameters that cannot be measured directly and provides those values in an output file that is imported to the Excel spreadsheet. Similarly, the profiler data from the Endeavor Island system are processed by the technique developed by Bart Brashers to provide two additional parameters, a mixing height and a potential temperature gradient. The profiler data are not available for all locations and times, so empirical relationships were developed by Bart Brashers to allow estimation of the profiler parameters when the profiler data are not available. The profiler data are also imported to the spreadsheet. The spreadsheet does the final calculations and prepares the .sfc and .pfl file.



Flowchart for COARE Process When Used to Replace AERMET

There are four cases examined here:

1. Beaufort Sea drilling locations using data from 2010 when the profiler data are available
2. Beaufort Sea drilling locations using data from 2009 when the profiler data are unavailable
3. Chukchi Sea drilling locations using data for 2010 when the profiler data are available
4. Chukchi Sea drilling locations using data for 2009 when the profiler data are unavailable

Each of these four cases was treated separately and the analysis is discussed below differently.

Beaufort Sea Using 2010 Data

Key Input Values for the COARE Algorithm:

Input Symbol	Description	Source of Data
	Latitude	For Beaufort 70.47
	Longitude	For Beaufort -148.36
	Mix ht. for gustiness calc.	200 m
U	Wind speed in m/s	Reindeer Island Monitor

tsea	Temp. of Sea Surface in deg C	Sivuliq Buoy
tair	Air Temp. in deg C	Sivuliq Buoy
RH	Relative Humidity in %	Sivuliq Buoy
Pres	Pressure in millibars	Reindeer Island Monitor
rs	Solar radiation in W/m^2	Reindeer Island Monitor
tsky	Sky cloud cover in tenths	Deadhorse
Ceil	Ceiling Height in 100's of feet	Deadhorse
Rain	Railfall in mm/hr	Deadhorse
zws	Height of the wind sensor in m	Always 10.7 m
ztbuoy	Height of the sensor on buoy in m	Always 3 m
zrh	Height of relative humidity sensor	Always 3 m
ts_depth	Depth of sea surface temp. meas.	Always 0.305 m (1 foot)

Calculated values hour by hour from COARE (COARE Output, imported to the spreadsheet)

Output 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
rf	Relative humidity	%
Wbar	Webb mean vertical velocity	m/s
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
qrs*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

Variables calculated in spreadsheet from COARE results

zu/L = zws/xmol

L_rev = limited Obukov length, where the absolute value of the Obukov length cannot be less than the critical value of 5.

Usr_rev = $usr(L\_rev/xmol)^{1/3}$

Zu/L_rev = zws/L_rev

PG stability class determined from xmol using following table

Lower Range of xmol	Upper Range of xmol	PG
-10	0	2
-25	-10	3
-∞	-25	4
25	∞	4
10	25	5
0	10	6

ZiVenk = either 2300*$Usr\_rev^{1.5}$ or 25, whichever is higher.

tau and venksm are calculated one hour to the next. Venksm is initially set (for the first hour) to ZiVenk, but subsequent hours calculated from tau and the previous hour's value for venksm. Tau is the previous hour of venksm divided by 2 times Usr_rev. Subsequent hours of venksm are calculated from the previous hours value of venksm times $e^{-3600/tau}$ plus ZiVenk times $(1-e^{-3600/tau})$.

Tvstar = $Usr\_rev^2(Tair+273.15)/(0.4*g*L\_rev)$

(g is gravitational acceleration = 9.808 m/s^2)

The following table describes the elements of the .pfl file and how each value is determined (these values are then exported from the spreadsheet in AERMOD format):

Parameter	Description	Source
yr,mo,dy,hr	Year, month, day, hour	Sequential
height10	Height of the wind meas. (m)	Always 10.7 m for Reindeer Island
last?		Always 1
dir10	Wind direction at 10 m (deg)	Reindeer Island
speed10	Wind speed at 10 m (m/s)	Reindeer Island
temp10	Temperature at 10 m (Deg C)	Reindeer Island
SigTheta10	Sigma Theta at 10 m (deg)	Reindeer Island
SigW10	Sigma W at 10 m (deg)	Reindeer Island

The following table describes the elements of the .sfc file and how each value is determined (these values are then exported from the spreadsheet in AERMOD format):

Parameter	Description	Source
Yr,mo,dy,jday,hr	Year, month, day, Julian day, hour	Sequential
SHF	Surface heat flux (W/m^2)	Hf from COARE output
ustar	Friction velocity (m/s)	Usr_rev from COARE output
wstar	Vertical friction velocity (m/s)	Based on L (below). If L >= 0 then wstar=-9, if L < 0 take maximum of 0 or $[-(ustar^3)(Zi\_conv)/(0.4L)]^{1/3}$

VPTG	Vertical potential temperature gradient	From the profiler but limited to be no greater than 0.005
Zi (Conv)	Mixing height (convective)	Only applicable for convective conditions (Z < 0) and then set equal to the profiler determined mixing height (see separate documentation on Brashers method of interpretation of 2010 actual profiler data).
Zi (mech)	Mixing height (mechanical)	From the profiler analysis but limited to no less than 25 m
L	Obukhov length (m)	L_rev from COARE output but limited to -8888 to 8888
z0	Roughness height (m)	From the COARE output (zo)
Bowen	Bowen Ratio	If SHF>0 and ef>0, Bowen=SHF/ef otherwise =0
Albedo	Albedo	Globally set to 0.055
Speed	Wind speed (m/s)	Reindeer Island
Direction	Wind direction	Reindeer Island
Zwind	Height of the wind sensor (m)	Always 10.7 m
Temp	Air Temperature (deg K)	Reindeer Island
Ztemp	Height of the temperature sensor (m)	Always 10 m
Prec code	Precipitation code	Not used 9999
Precip	Precipitation	Not used -9
RH	Relative humidity	Buoy
Press	Barometric pressure (mb)	Reindeer Island
CC	Cloud cover	Deadhorse

Beaufort Sea Using 2009 Data

Key Input Values for the COARE Algorithm:

Input Symbol	Description	Source of Data
	Latitude	For Beaufort 70.47
	Longitude	For Beaufort -148.36
	Mix ht. for gustiness calc.	200 m
U	Wind speed in m/s	Reindeer Island Monitor
tsea	Temp. of Sea Surface in deg C	Sivuliq Buoy
tair	Air Temp. in deg C	Sivuliq Buoy
RH	Relative Humidity in %	Sivuliq Buoy
Pres	Pressure in millibars	Reindeer Island Monitor
rs	Solar radiation in W/m^2	Reindeer Island Monitor
tsky	Sky cloud cover in tenths	Deadhorse
Ceil	Ceiling Height in 100's of feet	Deadhorse
Rain	Railfall in mm/hr	Deadhorse
zws	Height of the wind sensor in m	Always 10.7 m
ztbuoy	Height of the sensor on buoy in m	Always 1.4 m

zrh	Height of relative humidity sensor	Always 1.4 m
ts_depth	Depth of sea surface temp. meas.	Always 1.2 m

Calculated values hour by hour from COARE

Output 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
rf	Relative humidity	%
Wbar	Webb mean vertical velocity	m/s
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
qrs*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

Variables calculated in spreadsheet from COARE results

zu/L = zws/xmol

L_rev = limited Obukov length, where the absolute value of the Obukov length cannot be less than the critical value of 5.

Usr_rev = usr(L_rev/xmol)$^{1/3}$

Zu/L_rev = zws/L_rev

PG stability class determined from xmol using following table

Lower Range of xmol	Upper Range of xmol	PG
-10	0	2
-25	-10	3
-∞	-25	4
25	∞	4
10	25	5
0	10	6

ZiVenk = either 2300*$Usr\_rev^{1.5}$ or 25, whichever is higher.

tau and venksm are calculated one hour to the next. Venksm is initially set (for the first hour) to ZiVenk, but subsequent hours calculated from tau and the previous hour's value for venksm. Tau is the previous hour of venksm divided by 2 times Usr_rev. Subsequent hours of venksm are calculated from the previous hours value of venksm times $e^{-3600/tau}$ plus ZiVenk times $(1-e^{-3600/tau})$.

Tvstar = $Usr\_rev^2(Tair+273.15)/(0.4*g*L\_rev)$

(g is gravitational acceleration = 9.808 m/s^2)

The following table describes the elements of the .pfl file and how each value is determined:

Parameter	Description	Source
yr,mo,dy,hr	Year, month, day, hour	Sequential
height10	Height of the wind meas. (m)	Always 10.7 m for Reindeer Island
last?		Always 1
dir10	Wind direction at 10 m (deg)	Reindeer Island
speed10	Wind speed at 10 m (m/s)	Reindeer Island
temp10	Temperature at 10 m (Deg C)	Reindeer Island
SigTheta10	Sigma Theta at 10 m (deg)	Reindeer Island
SigW10	Sigma W at 10 m (deg)	Reindeer Island

The following table describes the elements of the .sfc file and how each value is determined:

Parameter	Description	Source
Yr,mo,dy,jday,hr	Year, month, day, Julian day, hour	Sequential
SHF	Surface heat flux (W/m^2)	Hf from COARE output
ustar	Friction velocity (m/s)	Usr_rev from COARE output
wstar	Vertical friction velocity (m/s)	Based on L (below). If L >= 0 then wstar=-9, if L < 0 take maximum of 0 or $[-(ustar^3)(Zi\_conv)/(0.4L)]^{1/3}$
VPTG	Vertical potential temperature gradient	Assigned monthly as the average of Barter Island and Barrow station data for each month (0.021 for August and 0.019 for September and October)
Zi (Conv)	Mixing height (convective)	Only applicable for convective conditions (Z < 0) and then calculated from Bart Bashers' statistical relationship (see separate documentation on Brashers method of interpretation of 2010 actual profiler data).
Zi (mech)	Mixing height (mechanical)	From the Bart Brashers' empirical relationship but limited to no less than 25 m

L	Obukhov length (m)	L_rev from COARE output but limited to -8888 to 8888
z0	Roughness height (m)	From the COARE output (zo)
Bowen	Bowen Ratio	If SHF>0 and ef>0, Bowen=SHF/ef otherwise =0
Albedo	Albedo	Globally set to 0.055
Speed	Wind speed (m/s)	Reindeer Island
Direction	Wind direction	Reindeer Island
Zwind	Height of the wind sensor (m)	Always 10.7 m
Temp	Air Temperature (deg K)	Reindeer Island
Ztemp	Height of the temperature sensor (m)	Always 10 m
Prec code	Precipitation code	Not used 9999
Precip	Precipitation	Not used -9
RH	Relative humidity	Buoy
Press	Barometric pressure (mb)	Reindeer Island
CC	Cloud cover	Deadhorse

Chukchi Sea Using 2010 Data

Key Input Values for the COARE Algorithm:

Input Symbol	Description	Source of Data
	Latitude	For Chukchi 71.51
	Longitude	For Chukchi -164.08
	Mix ht. for gustiness calc.	200 m
U	Wind speed in m/s	Chukchi Buoy
Tsea	Temp. of Sea Surface in deg C	Chukchi Buoy
Tair	Air Temp. in deg C	Chukchi Buoy
RH	Relative Humidity in %	Chukchi Buoy
Pres	Pressure in millibars	Point Lay Station (Chukchi Buoy when Pt. Lay missing)
Rs	Solar radiation in W/m^2	Point Lay Station (Chukchi Buoy when Pt. Lay missing)
Tsky	Sky cloud cover in tenths	Wainwright
Ceil	Ceiling Height in 100's of feet	Wainwright
Rain	Rainfall in mm/hr	Wainwright
Zws	Height of the wind sensor in m	Always 3.3 m
Ztbuoy	Height of the sensor on buoy in m	Always 3 m
Zrh	Height of relative humidity sensor	Always 3 m
ts_depth	Depth of sea surface temp. meas.	Always 0.305 m (1 foot)

Calculated values hour by hour from COARE

Output 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
Rf	Relative humidity	%
Wbar	Webb mean vertical velocity	m/s
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
qrs*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

Variables calculated in spreadsheet from COARE results

zu/L = zws/xmol

L_rev = limited Obukov length, where the absolute value of the Obukov length cannot be less than the critical value of 5.

Usr_rev = usr$(\text{L_rev}/\text{xmol})^{1/3}$

Zu/L_rev = zws/L_rev

PG stability class determined from xmol using following table

Lower Range of xmol	Upper Range of xmol	PG
-10	0	2
-25	-10	3
-∞	-25	4
25	∞	4
10	25	5
0	10	6

ZiVenk = either 2300*Usr_rev$^{1.5}$ or 25, whichever is higher.

tau and venksm are calculated one hour to the next. Venksm is initially set (for the first hour) to ZiVenk, but subsequent hours calculated from tau and the previous hour's value for venksm. Tau is the previous hour of venksm divided by 2 times Usr_rev. Subsequent hours of venksm are calculated from the previous hours value of venksm times $e^{-3600/tau}$ plus ZiVenk times $(1-e^{-3600/tau})$.

Tvstar = $Usr\_rev^2(Tair+273.15)/(0.4*g*L\_rev)$

(g is gravitational acceleration = 9.808 m/s^2)

The following table describes the elements of the .pfl file and how each value is determined. Note there were two records of data provide for each hour, since the temperature and winds are measuredon the buoy at different heights.

Parameter	Description	Source
yr,mo,dy,hr	Year, month, day, hour	Sequential
height10	Height of the wind meas. (m)	Always 3.0 m for the temperature and 3.3 m for the wind data
last?		0 for the first record and 1 for the second record
dir10	Wind direction at 10 m (deg)	On second record, data from the Buoy
speed10	Wind speed at 10 m (m/s)	On second record, data from Buoy
temp10	Temperature at 10 m (Deg C)	On first record, data from Buoy
SigTheta10	Sigma Theta at 10 m (deg)	Always 999.0
SigW10	Sigma W at 10 m (deg)	Always 99.0

The following table describes the elements of the .sfc file and how each value is determined (example Beaufort 2010)

Parameter	Description	Source
Yr,mo,dy,jday,hr	Year, month, day, Julian day, hour	Sequential
SHF	Surface heat flux (W/m^2)	Hf from COARE output
Ustar	Friction velocity (m/s)	Usr_rev from COARE output
Wstar	Vertical friction velocity (m/s)	Based on L (below). If L >= 0 -9, if L < 0 take maximum of 0 or $[-(ustar^3)(Zi\_conv)/(0.4L)]^{1/3}$
VPTG	Vertical potential temperature gradient	Assigned monthly as the average of Barter Island and Barrow station data for each month (0.021 for July and August and 0.019 for September and October)
Zi (Conv)	Mixing height (convective)	Only applicable for convective conditions (Z < 0) and then calculated from Bart Bashers' statistical relationship (see separate documentation on Brashers method of interpretation of 2010 actual profiler data).
Zi (mech)	Mixing height (mechanical)	From the Bart Brashers' empirical relationship but limited to no less than 25 m
L	Obukhov length (m)	L_rev from COARE output but limited to -8888 to 8888
z0	Roughness height (m)	From the COARE output (zo)
Bowen	Bowen Ratio	If SHF>0 and ef>0, Bowen=SHF/ef otherwise =0
Albedo	Albedo	Globally set to 0.055

Speed	Wind speed (m/s)	Chukchi Buoy
Direction	Wind direction	Chukchi Buoy
Zwind	Height of the wind sensor (m)	Always 3.3 m
Temp	Air Temperature (deg K)	Chukchi Buoy
Ztemp	Height of the temperature sensor (m)	Always 3 m
Prec code	Precipitation code	Not used 9999
Precip	Precipitation	Not used -9
RH	Relative humidity	Chukchi Buoy
Press	Barometric pressure (mb)	Point Lay (Chukchi Buoy when Pt. Lay not available)
CC	Cloud cover	Wainwright

Chukchi Sea Using 2009 Data

Key Input Values for the COARE Algorithm:

Input Symbol	Description	Source of Data
	Latitude	For Chukchi 71.51
	Longitude	For Chukchi -164.08
	Mix ht. for gustiness calc.	200 m
U	Wind speed in m/s	Chukchi Buoy (Beaufort Buoy when Chukchi Buoy not available)
Tsea	Temp. of Sea Surface in deg C	Chukchi Buoy (Beaufort Buoy when Chukchi Buoy not available)
Tair	Air Temp. in deg C	Chukchi Buoy (Beaufort Buoy when Chukchi Buoy not available)
RH	Relative Humidity in %	Chukchi Buoy (Beaufort Buoy when Chukchi Buoy not available)
Pres	Pressure in millibars	Wainwright Station
Rs	Solar radiation in W/m^2	Chukchi Buoy (Beaufort Buoy when Chukchi Buoy not available)
Tsky	Sky cloud cover in tenths	Wainwright
Ceil	Ceiling Height in 100's of feet	Wainwright
Rain	Rainfall in mm/hr	Wainwright
Zws	Height of the wind sensor in m	Either 10.7 m or 3.3 m depending on whether Beaufort data used or Chukchi Buoy
Ztbuoy	Height of the sensor on buoy in m	Either 1.4 m if Beaufort Buoy used or 3 m if Chukchi Buoy used
Zrh	Height of relative humidity sensor	Either 1.4 m if Beaufort Buoy used or 3 m if Chukchi Buoy used
ts_depth	Depth of sea surface temp. meas.	Either 1.2 m if Beaufort Buoy used or 0.305 m if Chukchi Buoy used

Calculated values hour by hour from COARE

Output 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
Rf	Relative humidity	%
Wbar	Webb mean vertical velocity	m/s
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
qrs*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

Variables calculated in spreadsheet from COARE results

zu/L = zws/xmol

L_rev = limited Obukov length, where the absolute value of the Obukov length cannot be less than the critical value of 5.

Usr_rev = usr(L_rev/xmol)$^{1/3}$

Zu/L_rev = zws/L_rev

PG stability class determined from xmol using following table

Lower Range of xmol	Upper Range of xmol	PG
-10	0	2
-25	-10	3
-∞	-25	4
25	∞	4
10	25	5
0	10	6

ZiVenk = either 2300*Usr_rev$^{1.5}$ or 25, whichever is higher.

tau and venksm are calculated one hour to the next. Venksm is initially set (for the first hour) to ZiVenk, but subsequent hours calculated from tau and the previous hour's value for venksm. Tau is the previous hour of venksm divided by 2 times Usr_rev. Subsequent hours of venksm are calculated from the previous hours value of venksm times $e^{-3600/tau}$ plus ZiVenk times ($1-e^{-3600/tau}$).

Tvstar = $Usr\_rev^2(Tair+273.15)/(0.4*g*L\_rev)$

(g is gravitational acceleration = 9.808 m/s^2)

The following table describes the elements of the .pfl file and how each value is determined. Note there were two records of data provide for each hour, since the temperature and winds are measured on the buoy at different heights. Also, different buoy data are used in different cases.

Parameter	Description	Source
yr,mo,dy,hr	Year, month, day, hour	Sequential
height10	Height of the wind meas. (m)	If Beaufort data are used, 1.4 m for the temperature and 10.7 m for the winds. If Chukchi data are used, 3.0 m for the temperature and 3.3 for the winds.
last?		0 for the first record and 1 for the second record
dir10	Wind direction at 10 m (deg)	On second record, data from the Buoy or from the Beaufort data when Chukchi is missing
speed10	Wind speed at 10 m (m/s)	On second record, data from the Buoy or from the Beaufort data when Chukchi is missing
temp10	Temperature at 10 m (Deg C)	On first record, data from the Buoy or from the Beaufort data when Chukchi is missing
SigTheta10	Sigma Theta at 10 m (deg)	Always 999.0
SigW10	Sigma W at 10 m (deg)	Always 99.0

The following table describes the elements of the .sfc file and how each value is determined (example Beaufort 2010)

Parameter	Description	Source
Yr,mo,dy,jday,hr	Year, month, day, Julian day, hour	Sequential
SHF	Surface heat flux (W/m^2)	Hf from COARE output
Ustar	Friction velocity (m/s)	Usr_rev from COARE output
Wstar	Vertical friction velocity (m/s)	Based on L (below). If L >= 0 -9, if L < 0 take maximum of 0 or $[-(ustar^3)(Zi\_conv)/(0.4L)]^{1/3}$
VPTG	Vertical potential temperature gradient	Assigned monthly as the average of Barter Island and Barrow station data for each month (0.021 for July and August and 0.019 for September and October)
Zi (Conv)	Mixing height (convective)	Only applicable for convective conditions (Z < 0) and then calculated from Bart Bashers' statistical relationship (see separate documentation on Brashers method of interpretation of 2010 actual profiler data).

Zi (mech)	Mixing height (mechanical)	From the Bart Brashers' empirical relationship but limited to no less than 25 m
L	Obukhov length (m)	L_rev from COARE output but limited to -8888 to 8888
z0	Roughness height (m)	From the COARE output (zo)
Bowen	Bowen Ratio	If SHF>0 and ef>0, Bowen=SHF/ef otherwise =0
Albedo	Albedo	Globally set to 0.055
Speed	Wind speed (m/s)	From the .pfl value above
Direction	Wind direction	From the .pfl value above
Zwind	Height of the wind sensor (m)	10.7 m when Beaufort data are used, 3.3 m when Chukchi Buoy data are available.
Temp	Air Temperature (deg K)	From the .pfl value above
Ztemp	Height of the temperature sensor (m)	1.4 m when Beaufort data are used, 3.0 m when Chukchi Buoy data are available.
Prec code	Precipitation code	Not used 9999
Precip	Precipitation	Not used -9
RH	Relative humidity	Chukchi Buoy (Beaufort Buoy when Chukchi Buoy not available)
Press	Barometric pressure (mb)	Wainwright Station
CC	Cloud cover	Wainwright Station

Attachment B

COARE-AERMOD Sensitivity Analysis of Evaluation Data Sets

Case 1

Sensitivity Analysis for Mixing Height Limits

Shell has provided EPA Region 10 with the results of a model evaluation for the COARE-AERMOD system. During the review of that model evaluation, EPA has raised a question about the sensitivity of the model evaluation results to a limit imposed on the mixing height. In the model evaluation submitted by Shell in December of 2010, all mixing heights were limited to be no less than 25 meters. In an email from Herman Wong of EPA Region 10 to Kirk Winges of ENVIRON dated March 10, 2011, EPA asked Shell to:

> "…please conduct a Case 1 sensitivity analysis using all three tracer gas experiments with the following minimum mechanical mixing height: 0 m, 5 m, and 15m."

In a subsequent email from Kirk Winges in response to the above-referenced email, it was mentioned that all mixing heights for the Cameron, Louisiana experiments were above 25 meters, without the external requirement limiting their value. Accordingly, the model for those cases would be entirely insensitive to the specified limits on mixing height. For the other two experiments, Pismo Beach, CA and Carpinteria, CA, there were mixing heights calculated in the Case 1 analysis less than 25 m, so a sensitivity analysis was conducted as requested. Table 1 summarizes the results of this analysis. Figure 1 is a scatter plot of these data and Figure 2 is a Q-Q plot of these data.

The results of the analysis show the main difference between the different limits on mixing height occur with the higher concentrations. The model performance in the upper concentrations degrades with lower limits on mixing height.

Table 1. Results of Model Sensitivity Analysis for Limits on Mixing Height						
Experiment	Date	Observed Conc. (ug/m3)	Conc. With No Limit on Mix Ht. (ug/m3)	Conc. With 5 m Limit on Mix Ht. (ug/m3)	Conc. With 15 m Limit on Mix Ht. (ug/m3)	Conc. With 25 m Limit on Mix Ht. (ug/m3)
Pismo Beach	12/8/81 15:00	6.8	26.2	26.2	26.2	23.9
Pismo Beach	12/8/81 16:00	7.0	23.9	23.9	25.2	24.0
Pismo Beach	12/11/81 14:00	5.0	0.5	0.5	0.5	0.5
Pismo Beach	12/11/81 15:00	4.9	0.5	0.5	0.5	0.5
Pismo Beach	12/11/81 17:00	3.9	0.5	0.5	0.5	0.5
Pismo Beach	12/11/81 19:00	3.2	0.1	0.1	0.1	0.1
Pismo Beach	12/13/81 14:00	3.3	2.3	2.3	2.3	2.3
Pismo Beach	12/13/81 15:00	1.9	1.6	1.6	1.6	1.6
Pismo Beach	12/13/81 17:00	3.5	2.5	2.5	2.5	2.5
Pismo Beach	12/14/81 13:00	9.2	4.8	4.8	4.8	4.8
Pismo Beach	12/14/81 15:00	4.5	1.3	1.3	1.3	1.3
Pismo Beach	12/14/81 17:00	5.6	2.2	2.2	2.2	2.2
Pismo Beach	12/15/81 13:00	1.8	1.3	1.3	1.3	1.3
Pismo Beach	12/15/81 14:00	0.9	0.7	0.7	0.7	0.7
Pismo Beach	12/15/81 19:00	4.2	4.1	4.1	2.1	3.0
Pismo Beach	6/21/82 15:00	4.8	23.1	23.1	23.1	23.1
Pismo Beach	6/21/82 16:00	2.3	27.6	27.6	27.6	27.6
Pismo Beach	6/21/82 17:00	2.7	25.0	25.0	25.0	24.3
Pismo Beach	6/21/82 18:00	4.4	7.4	7.4	7.4	7.4
Pismo Beach	6/22/82 15:00	4.6	19.3	19.3	19.3	19.3
Pismo Beach	6/22/82 16:00	2.9	15.1	15.1	15.1	15.1
Pismo Beach	6/22/82 19:00	2.7	14.8	14.8	14.8	14.8
Pismo Beach	6/24/82 13:00	1.5	3.0	3.0	3.0	3.0
Pismo Beach	6/24/82 15:00	2.3	3.7	3.7	3.7	3.7
Pismo Beach	6/25/82 12:00	7.8	17.1	17.1	17.1	17.1
Pismo Beach	6/25/82 13:00	4.5	12.7	12.7	12.7	12.7
Pismo Beach	6/25/82 15:00	2.3	1.9	1.9	1.9	1.9
Pismo Beach	6/25/82 16:00	3.7	4.8	4.8	4.8	4.8
Pismo Beach	6/25/82 17:00	2.9	4.5	4.5	4.5	4.5
Pismo Beach	6/27/82 16:00	2.6	1.9	1.9	1.9	1.9
Pismo Beach	6/27/82 18:00	2.8	1.6	1.6	1.6	1.6
Carpinteria	9/19/85 9:00	18.9	4.1	4.1	4.1	4.1
Carpinteria	9/19/85 10:00	21.4	7.1	7.1	7.1	7.1
Carpinteria	9/19/85 11:00	36.4	7.6	7.6	7.6	7.6
Carpinteria	9/19/85 12:00	22.4	3.3	3.3	3.3	3.3
Carpinteria	9/22/85 9:00	83.8	59.2	59.2	53.5	38.8

Carpinteria	9/22/85 10:00	87.8	90.2	90.2	78.0	50.0
Carpinteria	9/22/85 11:00	102.0	104.1	104.1	103.4	80.9
Carpinteria	9/22/85 11:00	102.0	44.0	44.0	44.2	43.9
Carpinteria	9/22/85 12:00	13.6	39.7	39.7	39.7	37.1
Carpinteria	9/22/85 12:00	13.6	7.2	7.2	7.2	8.0
Carpinteria	9/25/85 10:00	43.9	171.5	115.8	84.7	73.1
Carpinteria	9/25/85 11:00	78.5	499.7	310.4	226.7	153.8
Carpinteria	9/25/85 12:00	41.2	238.2	161.6	125.0	80.4
Carpinteria	9/25/85 13:00	108.8	190.2	118.2	124.9	116.1
Carpinteria	9/26/85 12:00	25.0	5.6	5.6	5.6	5.6
Carpinteria	9/26/85 13:00	7.6	4.7	4.7	4.7	4.7
Carpinteria	9/28/85 10:00	14.0	5.2	5.2	5.2	5.2
Carpinteria	9/28/85 10:00	14.0	4.4	4.4	4.4	4.4
Carpinteria	9/28/85 11:00	12.9	10.1	10.1	10.1	10.1
Carpinteria	9/28/85 11:00	12.9	8.8	8.8	8.8	8.8
Carpinteria	9/28/85 13:00	14.1	6.9	6.9	6.9	6.9
Carpinteria	9/28/85 13:00	14.1	7.0	7.0	7.0	7.0
Carpinteria	9/28/85 14:00	14.7	7.9	7.9	7.9	7.9
Carpinteria	9/28/85 14:00	14.7	7.3	7.3	7.3	7.3
Carpinteria	9/29/85 11:00	15.0	3.0	3.0	3.0	3.0
Carpinteria	9/29/85 12:00	20.6	11.1	11.1	11.1	11.1
Carpinteria	9/29/85 12:00	20.6	9.4	9.4	9.4	9.4

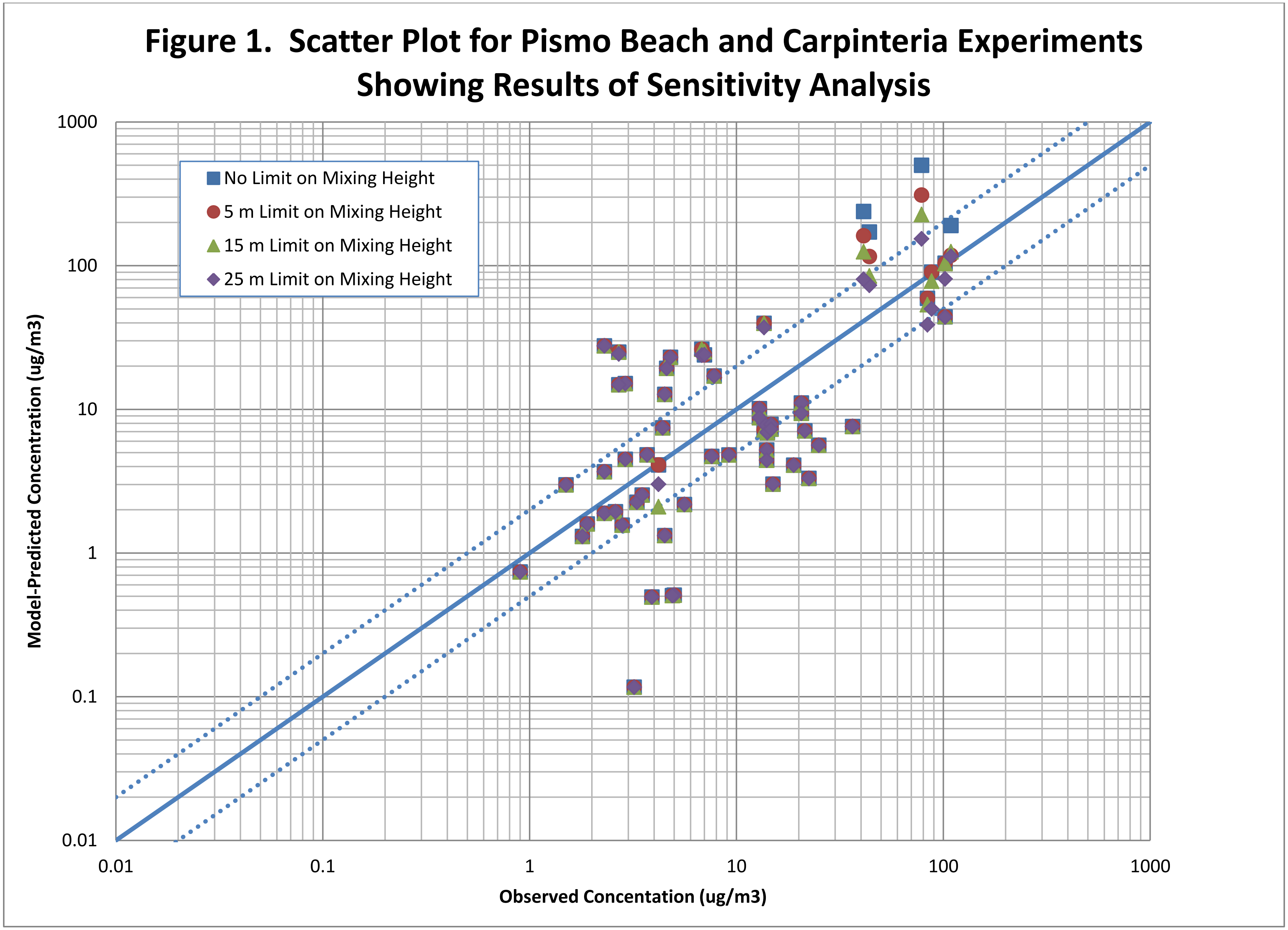


Figure 1. Scatter Plot for Pismo Beach and Carpinteria Experiments
Showing Results of Sensitivity Analysis
No Limit on Mixing Height
5 m Limit on Mixing Height
15 m Limit on Mixing Height
25 m Limit on Mixing Height
Model-Predicted Concentration (ug/m3)
Observed Concentation (ug/m3)
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
100
1000

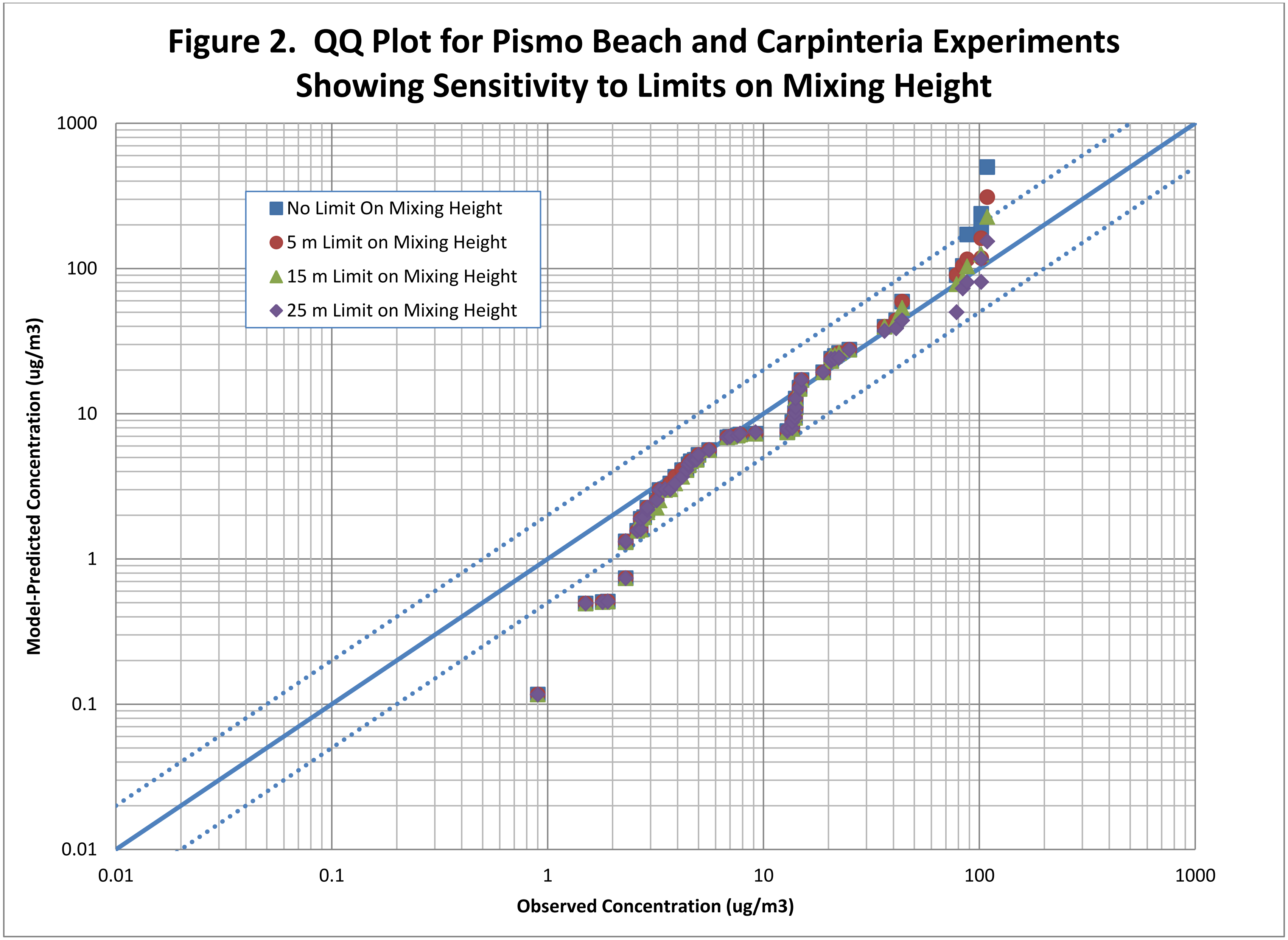


Figure 2. QQ Plot for Pismo Beach and Carpinteria Experiments
Showing Sensitivity to Limits on Mixing Height
No Limit On Mixing Height
5 m Limit on Mixing Height
15 m Limit on Mixing Height
25 m Limit on Mixing Height
Model-Predicted Concentration (ug/m3)
Observed Concentration (ug/m3)
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
100
1000

Attachment C

Glossary

Glossary

Absolute humidity

Absolute humidity on a volume basis is the quantity of water in a particular volume of air. The most common units are grams per cubic meter, although any mass unit and any volume unit could be used. Pounds per cubic foot is common in the U.S., and occasionally even other units mixing the Imperial and metric systems are used.

If all the water in one cubic meter of air were condensed into a container, the mass of the water in the container could be measured with a scale to determine absolute humidity. The amount of water vapor in that cube of air is the absolute humidity of that cubic meter of air. More technically, absolute humidity on a volume basis is the mass of dissolved water vapor, m_w, per cubic meter of total moist air, V_{net}:

$$AH = \frac{m_w}{V_{net}}.$$

Bulk Richardson number

A dimensionless number in meteorology relating vertical stability and vertical shear (generally, stability divided by shear). It represents the ratio of thermally produced turbulence and turbulence generated by vertical shear. Practically, its value determines whether convection is free or forced. High values indicate unstable and/or weakly-sheared environments; low values indicate weak instability and/or strong vertical shear. More technically, the Bulk Richardson Number is an approximation to the gradient Richardson number formed by approximating local gradients by finite difference across layers.

The bulk Richardson number R_B is

$$R_B = \frac{(g/T_v)\Delta\theta_v \Delta z}{(\Delta U)^2 + (\Delta V)^2},$$

where g is gravitational acceleration, T_v is absolute virtual temperature, $\Delta\theta_v$ is the virtual potential temperature difference across a layer of thickness Δz, and ΔU and ΔV are the changes in horizontal wind components across that same layer.

COARE bulk air-sea flux

The transfer of energy across the air-sea interface is an important meteorological parameter in defining the behavior of the atmosphere over large water bodies. The acronym COARE refers to the Coupled Ocean Atmosphere Response Experiment, an international research program that studies the interaction or coupling of the ocean and atmosphere in the western Pacific warm pool region. In 1993, Chris Fairall, Frank Bradley and David Rogers began development of a bulk air-sea flux algorithm for use by the COARE community. Version 1.0 was released in November 1993 and Version 2.0 in August of 1994.

The last major modifications to the algorithm were made at the COARE Air-Sea Interaction (Flux) Group Workshop in Honolulu, 2-4 August 1995. 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.

Version 2.5b was developed using COARE measurements that were limited to 0-12 m/s and the tropics. Data from higher latitudes and from studies with higher wind speeds resulted in the current version 3.0.

Convective mixing height

The vertical layers of the atmosphere closest to the surface are often called the "Boundary Layer" and are important in air pollutant modeling. Thermal effects, such as the heating and cooling of the ground from sunlight or the absence of sunlight are imparted to the lowest layer of the atmosphere. Under conditions where the ground is heating the air directly above the surface, this layer becomes unstable and there can be considerable vertical motion within the layer. This vertical motion tends to mix air pollutants and should be accounted for in any dispersion modeling. This layer is often termed the "convective layer" during conditions where the ground is imparting heat to the lower air. This convective process only extends above the ground to a certain height where more stable air is present. The height of this convective layer is termed the convective mixing height and is only present during convective conditions. At night, when the ground is no longer being heated by the air, the ground cools and cools the air above it, producing a more stable condition which is not convective and there is no convective mixing height.

Convective velocity scale

A velocity scale *w** for the convective mixed layer:

$$w^* = \left[\frac{g}{T_v} z_i \overline{w'\theta_v'}_s\right]^{1/3},$$

where *g* is gravitational acceleration, T_v is virtual temperature, z_i is average depth of the mixed layer, $\overline{w'\theta_v'}_s$ is the kinematic vertical turbulent flux of virtual potential temperature near the surface.

The velocity scale is typically on the order of 1 m s^{-1}, which is roughly the updraft speed in convective thermals. This scale is often used in similarity theories for the convective mixed layer and was previously known as the convective velocity scale.

Cool skin

The cool skin refers to the top molecular sublayer of the water surface. Practically, it is difficult to measure the actual temperature of this molecular layer, since it is so thin. Radiometric instruments can sense these ultra-thin layers, but practical ocean temperature instruments measure temperatures at some finite distance typically on the order of a few centimeters at the surface of the water.

Critical Richardson number

Turbulence in the atmosphere is critical in atmospheric dispersion modeling. The Richardson Number is a calculated meteorological parameter and has no physical analog, but is used to help define the vertical structure of turbulence in the atmosphere. More technically, the Richardson Number is a dimensionless ratio, Ri, related to the buoyant production or consumption of turbulence divided by the shear production of turbulence.

It is used to indicate dynamic stability and the formation of turbulence:

$$\mathrm{Ri} = \frac{\dfrac{g}{T_v}\,\dfrac{\partial\theta_v}{\partial z}}{\left(\dfrac{\partial U}{\partial z}\right)^2 + \left(\dfrac{\partial V}{\partial z}\right)^2},$$

where θ_v is virtual potential temperature, Tv is virtual temperature, z is height, g is gravitational acceleration, and (U, V) are the wind components toward the east and north. The critical Richardson number, Ric, is about 0.25 (although reported values have ranged from roughly 0.2 to 1.0), and flow is dynamically unstable and turbulent when $Ri < Ri_c$. Such turbulence happens either when the wind shear is great enough to overpower any stabilizing buoyant forces (numerator is positive), or when there is static instability (numerator is negative).

Dew point

The dew point is the temperature to which a given parcel of humid air must be cooled, at constant barometric pressure, for water vapor to condense into water.

Empirical relationships

Empirical relationships are mathematical relationships between parameters that are based on measurements or data. This is contrasted with theoretical relationships where two parameters are related by some law of nature.

*Friction velocity or u**

Any fluid such as air or water that flows over a surface will experience a force that is both imparted to the surface and imparted by the surface to the fluid. In the case of air, we often think of and refer to this process as “drag” where the stationary surface causes the air to slow down close to the surface. It is the reason that wind speeds are typically higher above ground than they are close to the ground. We call this force a “shear stress” close to the surface. The friction velocity is a meteorological parameter for expressing this shear stress. More technically, friction velocity is a form by which a shear stress may be re-written in units of velocity. It is useful as a method in fluid mechanics to compare true velocities, such as the velocity of a flow in a stream, to a velocity that relates shear between layers of flow.

Friction velocity is used to describe shear-related motion in moving fluids. It is used to describe:

- Diffusion and dispersion of particles, tracers, and contaminants in fluid flows
- The velocity profile near the boundary of a flow (see Law of the wall)
- Transport of sediment in a channel

Shear velocity also helps in thinking about the rate of shear and dispersion in a flow. A general rule is that the shear velocity is about 1/10 of the mean flow velocity.

$$u_\star = \sqrt{\frac{\tau}{\rho}}$$

Where τ is the shear stress in an arbitrary layer of fluid and ρ is the density of the fluid.

Marine boundary layer

The vertical layers of the atmosphere closest to the surface are often called the “Boundary Layer” and are important in air pollutant modeling. Marine Boundary Layer is simply a Boundary Layer in a marine environment, typically over the ocean or sea.

Monin-Obukhov length

The Monin-Obukhov Length is a meteorological parameter used to characterize stability in the lower layers of the atmosphere. More technically, the Obukhov length was first described by Alexander Obukhov[1] in 1946,[2] and therefore should not be called the Monin–Obukhov length, even though there is a Monin–Obukhov similarity theory that uses it.

The **Obukhov Length** is typically defined by

$$L = -\frac{u_*^3 \bar{\theta}_v}{kg(\overline{w'\theta_v'})_s}$$

where u_* is the frictional velocity, $\bar{\theta}_v$ is the mean virtual potential temperature, $(\overline{w'\theta_v'})_s$ is the surface virtual potential temperature flux, k is the von Kármán constant, and θ_* is a virtual potential temperature scale (k). This can be further reduced using the similarity theory approximation:

$$(\overline{w'\theta_v'})_s \approx -u_*\theta_*$$

to give:

$$L \approx \frac{u_*^2 \bar{\theta}_v}{kg\theta_*}.$$

The parameter θ * is proportional to $\bar{\theta}_v(z_r) - \bar{\theta}_v(z_{0,h})$ the vertical difference in potential virtual temperature. The greater $\bar{\theta}_v$ at $Z_{0,h}$ in comparison with its value at Z_r , the more negative the change in $\bar{\theta}_v$ with increasing height, and the greater the instability in the of the surface layer. In such cases, L is negative with a small magnitude, since it is inversely proportional to θ * . When L is negative with a small magnitude, $\frac{z}{L}$ is negative with a large magnitude. Such values of $\frac{z}{L}$ correspond to large instability due to buoyancy. Positive values of $\frac{z}{L}$ correspond to increasing $\bar{\theta}_v$ with height and stable stratification.

Relative humidity

Relative humidity is a measurement of the amount of water vapor in a mixture of air and water vapor. It is most commonly defined as the partial pressure of water vapor in the air-water mixture, given as a percentage of the saturated vapor pressure under those conditions. The relative humidity of air thus changes not only with respect to the absolute humidity (moisture content) but also temperature and pressure, upon which the saturated vapor pressure depends. Relative humidity is often used instead of absolute humidity in situations where the rate of water evaporation is important, as it takes into account the variation in saturated vapor pressure.

Sea surface temperature

The sea surface temperature is the measured temperature at the surface of the water. The very top layers of a water body have a number of sub layers, but sea surface temperature refers to the practically measured value of the surface of the water, which is typically a few centimeters below the actual sea surface.

Shoreline fumigation

Shoreline fumigation is an atmospheric mixing condition that is unique to shoreline settings. Air passing over a large land-sea surface interface, will change from a land-based system, where the diurnal heating of the ground affects the mixing conditions, to a marine system, where the air-sea surface temperature difference affects mixing close to the surface. In this transition from one area to another, plumes that were previously held aloft, typically within a deep stable layer with low amounts of mixing, can suddenly be affected by a more turbulent mixing environment, where pollutants are rapidly mixed to the surface. This process is termed “fumigation.”

Similarity theory

This term refers to Monin-Obukhov similarity theory, which is a relationship describing the vertical behavior of nondimensionalized mean flow and turbulence properties within the atmospheric surface layer (the lowest 10% or so of the atmospheric boundary layer) as a function of the Monin–Obukhov key parameters.

These key parameters are the height *z* above the surface, the buoyancy parameter ratio (g/Tv) of inertia and buoyancy forces, the kinematic surface stress (τ0), and the surface virtual temperature flux

$$Q_{v0} = H_{v0}/(\rho C_p) = \overline{w' T_{v0}},$$

where g is gravitational acceleration, T_v is virtual temperature, τ_0 is turbulent stress at the surface, is air density, Q_{v0} is a kinematic virtual heat flux at the surface, H_{v0} is a dynamic virtual heat flux at the surface, C_p is the specific heat of air at constant pressure, and $\overline{w' T_{v0}}$ is the covariance of vertical velocity w with virtual temperature near the surface. The key parameters can be used to define a set of four dimensional scales for the surface layer: 1) the friction velocity or shearing velocity, a velocity scale,

$$u_* = (\tau_0/\rho)^{1/2};$$

2) a surface-layer temperature scale,

$$T_{*SL} = Q_{v0}/u_*;$$

3) a length scale called the Obukhov length,

$$L = \frac{-u_*^3 T_v}{kgQ_{v0}},$$

where k is the von Kármán constant; and 4) the height above ground scale, z. These key scales can then be used in dimensional analysis to express all surface-layer flow properties as dimensionless universal functions of z/L. For example, the mean wind shear in any quasi-stationary, locally homogeneous surface layer can be written as

$$\frac{\partial U}{\partial z} = \frac{u_*}{z} f\left(\frac{z}{L}\right),$$

where f is a universal function of the dimensionless height z/L. The forms of the universal functions are not given by the Monin–Obukhov theory, but must be determined theoretically or empirically. Monin–Obukhov similarity theory is the basic similarity hypothesis for the horizontally homogeneous surface layer. With these equations and the hypothesis that the fluxes in the surface layer are uniform with height, the momentum flux, sensible heat flux, and fluxes of water vapor and other gases can be determined.

Skin temperature

The term skin temperature refers to the temperature of the thinnest layer of the sea surface. It has the same meaning as the "Cool Skin Temperature" discussed above.

Stable boundary layer height

Atmospheric mixing is important in air dispersion analyses. The layer of the atmosphere closest to the surface is called the boundary layer. The air is this layer can be thought of as unstable, neutral or stable, relating to the vertical temperature structure. Unstable conditions also called convective conditions mean there is considerable vertical mixing in the layer as a result of temperature differences in the air. Stable conditions occur when there is little vertical mixing and are typical of nighttime when the ground is cooler than the air and as a result causes the lower layers of air to be cooler than upper layers. A layer of this stable air exists on most nights and the height of this layer is the stable boundary layer height.

Stable mixing height

The stable mixing height is the height of the boundary layer during stable conditions or the stable boundary layer height.

Surface energy fluxes

Energy, in the form of radiation, heat from evaporation from a liquid surface, and mechanical from shear stress is transferred throughout the diurnal cycle. The amount of energy transferred per square unit of area of a surface is called the surface energy flux. It can be positive or negative, depending on whether the transfer is upwards or downwards.

Surface Rossby number

The time, space and velocity scales are important in determining the importance of the Coriolis effect. Whether rotation is important in a system can be determined by its Rossby number, which is the ratio of the velocity, *U*, of a system to the product of the Coriolis parameter, $f = 2\omega \sin \varphi$, and the length scale, *L*, of the motion:

$$Ro = \frac{U}{fL}.$$

The Rossby number is the ratio of inertial to Coriolis forces. A small Rossby number signifies a system which is strongly affected by Coriolis forces, and a large Rossby number signifies a system in which inertial forces dominate. For example, in tornadoes, the Rossby number is large, in low-pressure systems it is low and in oceanic systems it is of the order of unity. As a result, in tornadoes the Coriolis force is negligible, and balance is between pressure and centrifugal forces. In low-pressure systems, centrifugal force is negligible and balance is between Coriolis and pressure forces. In the oceans all three forces are comparable.

Surface roughness length

Roughness length (z_0) is a parameter of some vertical wind profile equations that model the horizontal mean wind speed near the ground; in the log wind profile, it is equivalent to the height at which the wind speed is zero. It is so named because it is typically related to the height of terrain roughness elements. Whilst it is not a physical length, it can be considered as a length-scale a representation of the roughness of the surface.

Vertical potential temperature gradient

Under normal conditions, temperature of the air decreases with height. However, in some cases, the temperature can increase and in most cases, it can vary with height. As a result, the variation of temperature with height is often termed a temperature profile. The potential temperature differs slightly from the actual temperature. The potential temperature of a parcel of fluid at pressure P is the temperature that the parcel would acquire if adiabatically brought to a standard reference pressure P_0, usually 1000 millibars. The potential temperature is denoted θ and, for air, is often given by

$$\theta = T\left(\frac{P_0}{P}\right)^{R/c_p},$$

where T is the current absolute temperature (in K) of the parcel, R is the gas constant of air, and cp is the specific heat capacity at a constant pressure. This equation is often known as Poisson's equation.

The vertical potential temperature gradient is the rate at which the potential temperature decreases with height, by comparison with two points.

Virtual potential temperature lapse rate

In most meteorological application, temperature is used as the measured or calculated temperature of the air. However, the density and physical properties of air are changed to a slight degree by the presences of water vapor. The term virtual temperature is an adaptation of the actual temperature to allow the same equations of state to be used for air, regardless of vapor content of the air. The virtual temperature is always slightly higher than the actual temperature. As described under the definition of vertical potential temperature gradient, there is an adaptation of the temperature, called the potential temperature is used to account for pressure changes at different elevations in the atmosphere. The same adjustment can be made to virtual temperatures. The term lapse rate, refers to the rate at which the temperature changes with height.

Virtual temperature

In most meteorological application, temperature is used as the measured or calculated temperature of the air. However, the density and physical properties of air are changed to a slight degree by the presences of water vapor. The term virtual temperature is an adaptation of the actual temperature to allow the same equations of state to be used for air, regardless of vapor content of the air. The virtual temperature is always slightly higher than the actual temperature.

Warm layer

In a large water body, there are several layers of water close to the surface. The skin or cool skin temperature refers to the near molecular layer of water on the immediate surface. The layer directly below, is called the warm layer because this layer is influenced by heating from the sun’s rays. The warm layer is the typical layer measured by many sea surface temperature measurements.

Well-developed or deep sea

In the context of the COARE algorithm, the terms “well-developed or deep sea” refer to an ocean surface state has reached equilibrium and is not close to shore where transitions can occur in water surface conditions. Rather, the well-developed or deep sea conditions are more uniform and steady as in the open sea.

Wet bulb temperature

The wet bulb temperature is a way of characterizing the amount of water vapor in the atmosphere. The term stems from a measurement technique called a “sling psychrometer” where two mercury temperature thermometers are mounted on a plate attached to a chain. One of the mercury thermometers is covered with a wet piece of gauze. The two thermometers are swung rapidly through the air for a period of time. The “dry bulb” thermometer will read the same value as it did in the air before the process. The wet bulb, however, will drop in temperature because as the gauze is swung through the air, water evaporates from the gauze. The evaporation of water draws energy from the gauze and the “wet bulb” thermometer will read a lower temperature than the dry bulb. Since the amount of water evaporating from the gauze will be a function of the water vapor concentration in the air (under dryer conditions, more water will evaporate and the temperature will drop to a greater degree), the wet bulb temperature is an indication of the water vapor content in the air. Equations are available for relating the wet bulb temperature to the specific and/or relative humidity.