Arnold Schwarzenegger
Governor

THE CENTRAL CALIFORNIA OZONE STUDY

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Prepared By:
Ajith Kaduwela, Ph.D.
Modeling and Meteorology Branch
Planning and Technical Support Division
California Air Resources Board
California Environmental Protection Agency
1001 I Street
Sacramento, California 95812

Contract No. 700-98-027

Prepared For:
California Energy Commission
Public Interest Energy Research (PIER) Program

Marla Mueller,
Contract Manager

Kelly Birkinshaw,
Program Area Team Lead

Martha Krebs, Ph.D.
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

B. B. Blevins
Executive Director

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PLANNING STUDY FOR POWER PLANT PLUME MEASUREMENTS DURING CCOS 2000

Final Report

Prepared by

Prakash Karamchandani
Krishnakumar Vijayaraghavan
Atmospheric & Environmental Research, Inc.
2682 Bishop Drive, Suite 120
San Ramon, CA 94583

Prepared for

San Joaquin Valleywide Air Pollution Study Agency
c/o California Air Resources Board
2020 L Street
Sacramento, CA 94812

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EXECUTIVE SUMMARY

As part of the Central California Ozone Study (CCOS), aircraft measurements of the evolution of the chemistry of power plant plumes will be conducted. The purpose of these measurements is to characterize the formation of ozone (O_3) and other secondary pollutants in the power plant plumes and their potential contribution to air pollution in the San Joaquin Valley (SJV). Two power plants have been selected for this study: the Pittsburg power plant located in the Sacramento river delta and the Moss Landing power plant located on the Pacific Coast near Monterey.

In order to optimize the results of the aircraft measurement program, it is important to identify the conditions under which the plumes of these two power plants can be characterized with sufficient reliability. It is also useful to know whether it is feasible to measure the plumes at downwind distances where O_3 formation starts to occur within the plume. This report presents results from a simulation study that provides quantitative information that can be used to help plan power plant plume aircraft measurements during CCOS. We used a state-of-the-science reactive plume model, SCICHEM, to simulate the evolution of the Pittsburg and Moss Landing plumes for a range of meteorological conditions (early morning, midday and afternoon) for atmospheric conditions conducive to plume transport into the SJV. We also conducted sensitivity studies to investigate the effect of plume downwash on the Pittsburg plume, the interaction of the Contra Costa power plant plume with the Pittsburg plume, and the effect of background pollution levels on plume chemistry.

The input meteorological and background concentration data for the simulations were obtained using the results of previous MM5 and SAQM simulations of an episode in August 1990. Because these simulations included the sources that were studied here, the background NO_x concentrations in our study are likely to be slightly higher than without these sources. The primary effect of this approximation is that we may underestimate the downwind distances at which the plume concentrations approach the background values.

The SCICHEM simulations indicate that the plume of the Moss Landing power plant undergoes more meandering and dispersion than the plume of the Pittsburg power plant because the terrain is more complex in the vicinity of Moss Landing. As a result,

the widths of the Moss Landing plume tend to be greater than those of the Pittsburg plume. The plume height of the Moss Landing plume was calculated to be between 100 and 220 m agl, depending on the time of day The plume height of the Pittsburg plume was affected by building downwash only during the morning hours and was calculated to be between 200 and 280 m agl.

The comparisons of the simulated plume concentrations of nitrogen oxides (NO_x and NO_2), O_3 and nitric acid (HNO_3) with typical background ambient concentrations suggest that the Moss Landing plume may be difficult to discern from the background beyond 40 to 50 km downwind from the plant. On the other hand, the simulations suggest that it may be possible to discern the Pittsburg plume from the background beyond 50 km (as far as 70 km) downwind from the plant.

Formation of O_3 in the plume was simulated in only one scenario: a Moss Landing plume at 4 p.m. where the plume O_3 concentration was 2 to 3 ppb above the background value at 75 km downwind. In all other scenarios, the plume O_3 concentration remained below the background value.

Formation of HNO_3 in excess of the background value was simulated in all cases. More HNO_3 was formed in the Moss Landing plume (up to 5 ppb above background at noon) than in the Pittsburg plume (up to 1 ppb above background at 4 p.m.).

The differences in plume chemistry between the Moss Landing and Pittsburg plumes are likely due to the fact that the Pittsburg NO_x emissions are released initially into a VOC-limited atmosphere whereas the Moss Landing NO_x emissions are released into a NO_x-limited atmosphere.

Doubling the background concentrations in the model simulations led to greater O_3 deficits in the plume (since more background O_3 was available for titration by plume NO) and about twice as much HNO_3 formation in the plume (due to greater oxidant levels in the background). Using higher background concentrations did not affect the general conclusions on the discernibility of the plumes against the background.

Joint simulations of the plumes from the Pittsburg and Contra Costa power plants (which are 12 km apart) indicate that the two plumes may overlap at their edges and may appear as a single wide plume.

The effect of plume downwash was simulated using the PRIME model to determine the change in plume height. This change was provided as a correction to the stack height in the SCICHEM simulations. The effect was negligible for the Moss Landing plume and minor for the Pittsburg plume. However, downwash may also affect the plume dilution near the source, and this could not be simulated within the SCICHEM framework.

1. INTRODUCTION

The Central California Ozone Study (CCOS) will be conducted during the summer of 2000. The objective of the study is to obtain a suitable database for grid-based, photochemical modeling. As part of the study, aircraft measurements of the evolution of the chemistry of power plant plumes will be conducted. The purpose of these measurements is to characterize the formation of ozone (O_3) and other secondary pollutants in the power plant plumes and their potential contribution to air pollution in the San Joaquin Valley (SJV). Two power plants have been selected for this study: the Pittsburg power plant located in the Sacramento river delta and the Moss Landing power plant located on the Pacific Coast near Monterey.

Aircraft measurements in power plant plumes are difficult because the incremental chemical concentrations (i.e., difference between plume concentrations and background concentrations) may be small compared to variations in the background concentrations (i.e., those concentrations outside the plume). Conditions with strong atmospheric dispersion will lead to dilute plumes that may be difficult to measure. Stable conditions, on the other hand, should preserve the integrity of the plumes farther downwind. In order to optimize the results of the aircraft measurement program, it is important to identify the conditions under which the plumes of these two power plants can be characterized with sufficient reliability. It is also useful to know whether it is feasible to measure the plumes at downwind distances where O_3 formation starts to occur within the plume.

This report presents results from a simulation study to develop the quantitative information required to plan power plant plume aircraft measurements during CCOS 2000. We used a state-of-the-science reactive plume model to simulate the evolution of the Pittsburg and Moss Landing plumes for a range of meteorological conditions (early morning, midday and afternoon) for atmospheric conditions conducive to plume transport into the SJV. We also conducted sensitivity studies to investigate the effect of plume downwash on the Pittsburg plume, the interaction of the Contra Costa power plant plume with the Pittsburg plume, and the effect of background pollution levels on plume chemistry.

Section 2 provides a brief description of the model used in this study and its previous performance evaluation using helicopter plume measurements conducted in the southeastern United States. The model simulations and results are described in Section 3. Section 4 summarizes the study and provides recommendations for conducting plume measurements during CCOS.

2. THE REACTIVE PLUME MODEL

The reactive plume model used in this study is the Second-order Closure Integrated puff model (SCIPUFF) with CHEMistry (SCICHEM). Plume transport and dispersion are simulated with SCIPUFF, a model that uses a second-order closure approach to solve the turbulent diffusion equations. SCIPUFF was originally developed and tested by Titan/ARAP under EPRI sponsorship as part of the Plume Model Validation and Development (PMV&D) project (Sykes et al., 1988). SCIPUFF was further developed under Defense Nuclear Agency (DNA) sponsorship to include a number of improvements, both in the description of the physical phenomena and also in the efficiency of the numerical computation. With additional funding from EPRI and the Defense Nuclear Agency (DNA), a capability to describe the evolving chemical composition of a dispersing scalar was included in SCIPUFF. This allows a general chemical reaction scheme to be specified, with an arbitrary number of species. This reactive version of the model is referred to as SCICHEM.

In SCIPUFF, the plume is represented by a collection of three-dimensional puffs that are advected and dispersed according to the local characteristics (wind speed and direction, turbulence) of the atmosphere. Thus, plume dispersion is not constrained by any geometric function but instead reflects the non-stationary non-homogeneous nature of atmospheric processes. A second-order turbulence closure scheme is used to parameterize turbulent diffusion, providing a direct connection between measurable velocity statistics and the predicted dispersion rates.

Each puff has a Gaussian representation of the concentrations of emitted inert species. The overall plume, however, can have any spatial distribution of these concentrations, since it consists of a multitude of puffs that are independently affected by the transport and dispersion characteristics of the atmosphere. SCIPUFF can simulate the effect of wind shear since individual puffs will evolve according to their respective locations in an inhomogeneous velocity field and since the full Gaussian spatial moment tensor is used, rather than just the diagonal moments. As puffs grow larger, they may encompass a volume that cannot be considered homogenous in terms of the meteorological variables. A puff splitting algorithm accounts for such conditions by

dividing puffs that have become too large into more smaller puffs. Conversely, puffs may overlap significantly, thereby leading to an excessive computational burden. A puff merging algorithm allows individual puffs that are similar in size and location and, therefore, are affected by the same (or very similar) micro-scale meteorology, to combine into a single puff. Also, the effects of buoyancy on plume rise and initial dispersion are simulated by solving the conservation equations for mass, heat, and momentum.

The chemical reactions within the puffs are simulated using a general framework that allows any chemical kinetic mechanism to be treated. The user enters the chemical reactions and their associated rate parameters, and SCICHEM sets the corresponding system of ordinary differential equations (ODE) to be solved. Chemical species concentrations in the puffs are treated as perturbations from the background concentrations. The formulation of nonlinear chemical kinetics within the puff framework has been described by Sykes et al. (1997). The effect of turbulence on chemical kinetics can be simulated explicitly (the user selects the reactions for which the turbulent kinetic term is simulated).

The puff chemistry can also be simulated using a staged chemical kinetic mechanism where the number of reactions treated increases as the puff mixes with background air (Karamchandani et al., 1998). This multistage approach offers reasonable accuracy (within 10%) with increased computational speed.

Karamchandani et al. (2000) conducted an evaluation of SCICHEM using helicopter power plant plume measurements from the 1995 Southern Oxidants Study (SOS) Nashville/Middle Tennessee Ozone Study. The model was applied for 6 days in June and July of 1995 and the model's ability to estimate physical and chemical plume characteristics, such as plume width and reactive species concentrations, was evaluated using the helicopter measurements.

Recent improvements to SCICHEM include the incorporation of modules for aerosol thermodynamics and aqueous-phase chemistry (Santos et al., 1999; 2000). The aerosol thermodynamic module is based on SCAPE2, originally developed by Meng et al. (1995). SCAPE2 simulates the equilibrium phase distribution of sulfuric acid, sulfate, nitric acid, nitrate, ammonia, ammonium, sodium, potassium, calcium, magnesium, chloride, hydrochloric acid, carbonate and carbon dioxide. The aqueous-phase chemistry

module incorporated in SCICHEM is based on the model developed by Strader et al. (1998). This model includes 17 gas-aqueous equilibrium reactions, 17 aqueous equilibrium reactions, and 99 aqueous kinetic reactions among 18 gas-phase species and 28 aqueous-phase species. The gas-phase version of SCICHEM was used in this study.

3. SIMULATIONS AND RESULTS

3.1 Description of Simulations

We selected August 6, 1990 for our simulations, since the flow was generally westerly to northwesterly on this day. This allowed us to simulate the transport of the Pittsburg power plant plume into the SJV as well as to investigate its interaction with the Contra Costa power plant plume (see below).

Base case simulations for the Moss Landing and Pittsburg power plants were conducted for 3 meteorological situations: early morning, mid-day, and late afternoon. We conducted 3 sets of simulations, each of 6 hours duration, ending at 8 a.m., 12 noon and 4 p.m. on August 6. To locate the plume centerlines, we placed samplers in a three-dimensional radial grid at 1.8 degree intervals and 20 m vertical resolution (from the surface to 1000 m agl) and various downwind distances to about 75 km from each source.

In addition to the base simulations, we conducted the following sensitivity studies:

- Effect of building downwash – buildings in the vicinity of short stacks can influence the plume rise and dispersion of plumes from these stacks. Because SCICHEM does not currently include a treatment of building downwash, we used a model developed by Schulman et al. (2000), referred to as the Plume Rise Model Enhancements (PRIME), to determine the importance of building downwash. We used building configuration data supplied by the California Energy Commission (CEC) for the two power plants. The results from PRIME showed that building downwash was unimportant for Moss Landing, and only slightly important for Pittsburg. In a sensitivity study with SCICHEM, we used the PRIME results to adjust stack parameters for Pittsburg.
- Interaction of the Pittsburg power plant plume with the Contra Costa power plant plume – the Contra Costa power plant is located about 11.4 km to the east and 2.5 km to the south of the Pittsburg power plant. Under westerly and

north-westerly flow conditions, the plumes from the two plants will overlap. We conducted a sensitivity study to investigate this interaction by simulating the Contra Costa power plant plume in addition to the Moss Landing and Pittsburg plumes.

- Effect of background concentrations – we conducted a study to investigate the sensitivity of the results to a doubling of the base case background concentrations of all species.

3.2 Development of Model Inputs

To ensure that the data used to drive the model are representative of the local environment of the Moss Landing and Pittsburg power plants, we used outputs from the MM5 and SAQM simulations of the August 3-6, 1990 episode (provided by the California Air Resources Board) to develop the meteorological and background chemical concentrations needed as input for the simulations. Processors were developed to read the SAQM M1 and M2 meteorology files and C1 and C2 concentration files and create the files required for the SCICHEM simulations. The SAQM files used for our simulations were those for the 12 km horizontal resolution domain with 35x42 horizontal grid points and 15 vertical layers.

The California Energy Commission (CEC) provided emissions and source characteristics of the power plants. CEC also provided adjacent building configuration data for the building downwash calculations. We used conditions typical for the plants operating at full load during a typical summer day – the total NO_x (as NO_2) emissions for Moss Landing, Pittsburg and Contra Costa were about 1150 lbs/hr, 1818 lbs/hr, and 550 lbs/hr, respectively. We assumed that 90% of the NO_x emissions were emitted as NO (on a molar basis) for all three plants.

Note that the SAQM concentrations used as input to SCICHEM include the contributions of the power plants studied here. The scope of this study did not allow us to perform new SAQM simulations to develop background concentrations that did not include the NO_x emissions from these power plants. Thus, the background NO_x concentrations used in our study will be slightly higher than the background

concentrations without these sources. These differences are expected to be negligible near the source, where the plume NO_x concentrations are an order of magnitude or more higher than background values. At larger downwind distances, we will tend to err on the conservative side on the feasibility of tracking the plume as a result of this approximation.

3.3 Base Case Results

3.3.1 Plume dispersion

The results are presented for the end of each 6-hour period simulated by SCICHEM: 2 a.m. to 8 a.m., 6 a.m. to 12 noon, and 10 a.m. to 4 p.m. We begin by discussing the vertically integrated tracer concentrations predicted by the model at the end of each 6 hour period to determine the general transport of the Moss Landing and Pittsburg plumes. This tracer is a fictitious non-reactive and non-depositing material released from each source at a rate of 1000 g/s.

Figure 3-1 shows the vertically integrated tracer concentrations at 8 a.m. due to the two sources. The Moss Landing power plant is located approximately 130 km south and 8 km east of the Pittsburg power plant. The Moss Landing plume is primarily traveling to the southeast although there is a split in the flow direction at about 50 km from the plant, with part of the plume going toward the northeast.

The Pittsburg plume is narrower than the Moss Landing plume and is traveling steadily in an east-southeasterly direction. The average plume centerline height for both plumes is about 220 m agl, but there is more variation in the Moss Landing plume height as compared to the Pittsburg plume as the plumes move downwind of the stacks. From Figure 3-2, which shows the terrain features for the domain, we see that the Pittsburg plume is primarily traveling over flat terrain, while the Moss Landing plume encounters the Coastal Range quickly.

Vertically integrated tracer concentrations for the two plumes at noon are shown in Figure 3-3. As in the 8 a.m. results, we see a lot more variation in the direction of the Moss Landing plume as compared to the Pittsburg plume. The Moss Landing plume is

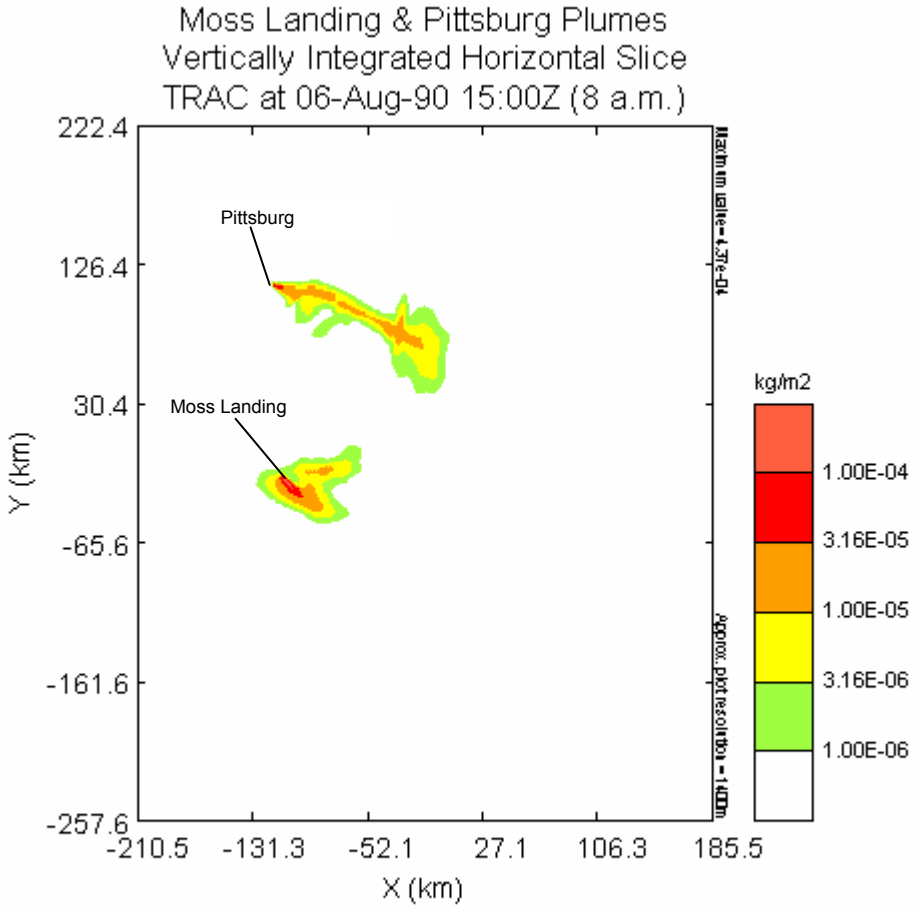

Figure 3-1. Vertically integrated tracer concentrations from the Moss Landing and Pittsburg power plants at 8 a.m. on August 6, 1990.

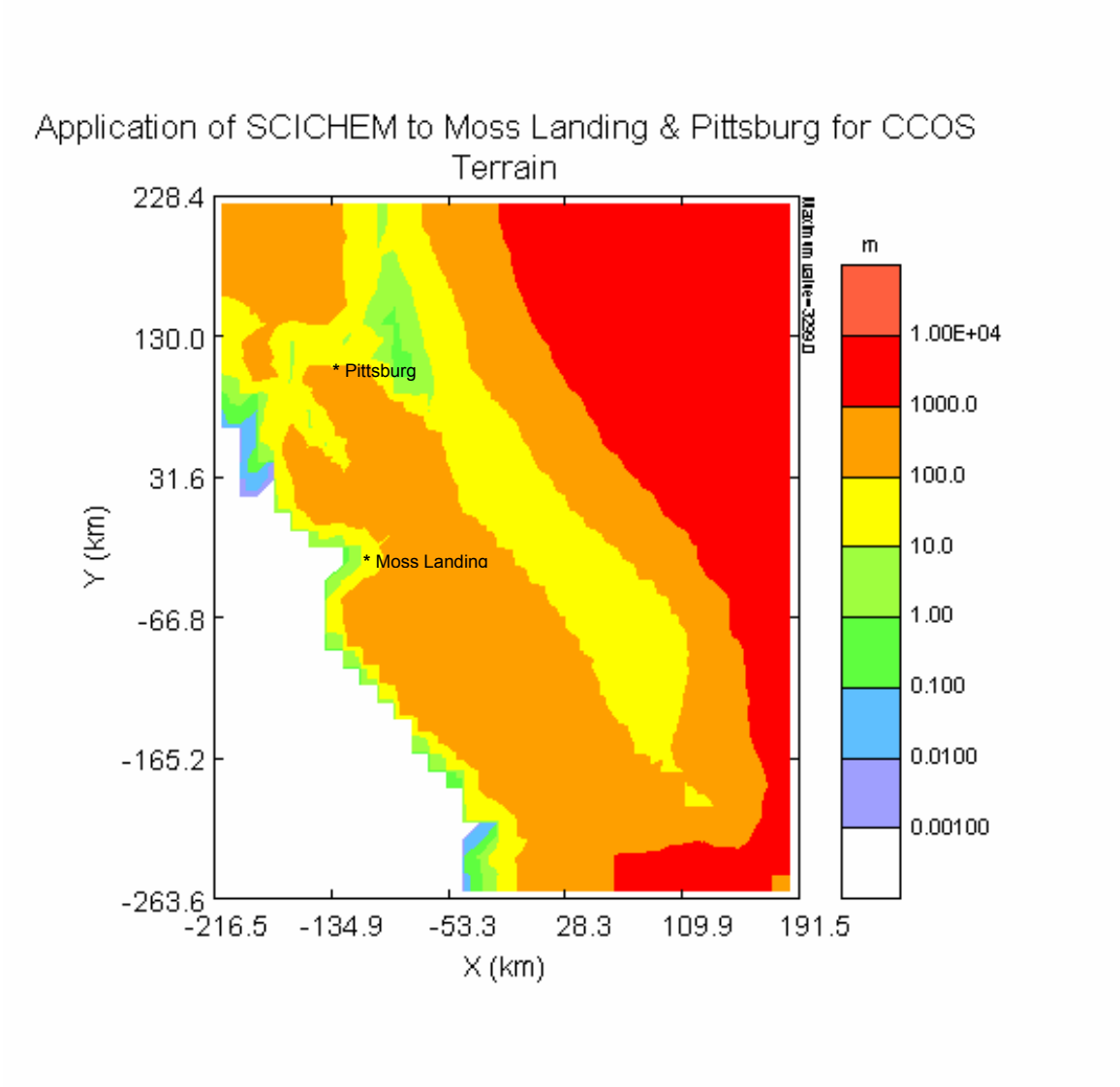

Figure 3-2. Terrain features in the SARMAP Air Quality Model Domain.

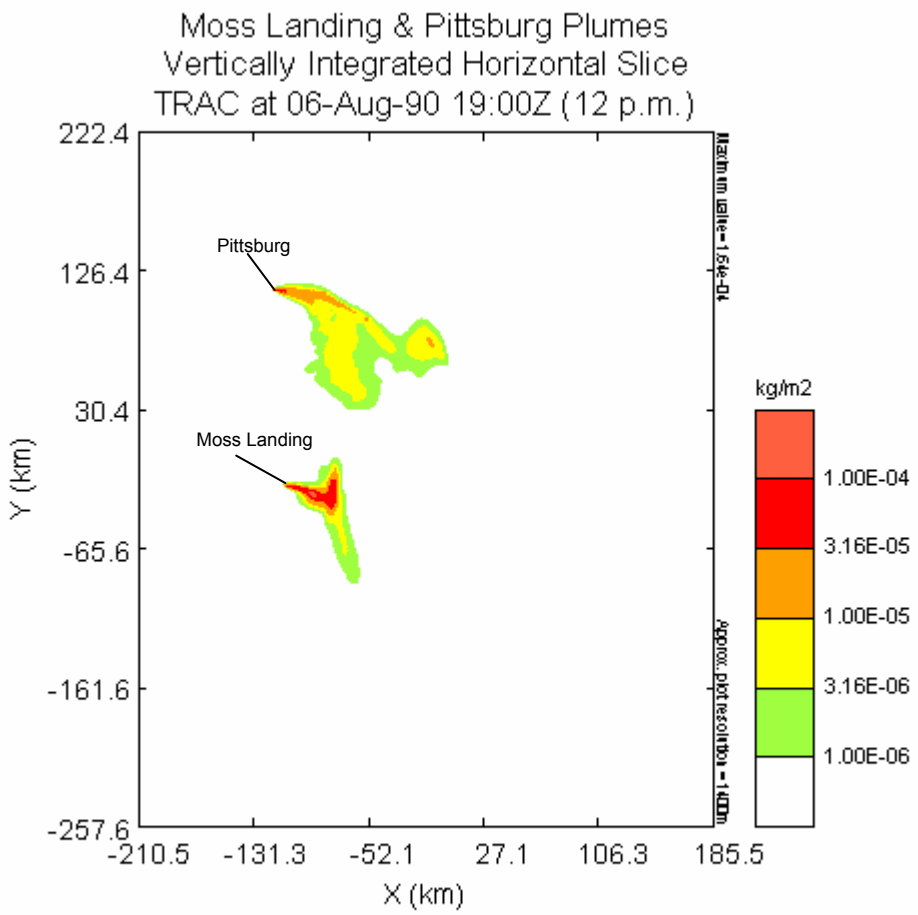

Figure 3-3. Vertically integrated tracer concentrations from the Moss Landing and Pittsburg power plants at 12 noon on August 6, 1990.

initially traveling towards the east-southeast, but travels in a more southerly direction at about 50 km from the source. Part of the plume is also traveling toward the northeast. The Pittsburg plume, on the other hand, is more or less steadily traveling towards the east-southeast. The average plume centerline height for the Moss Landing plume is about 145 m agl, as compared to the Pittsburg plume centerline height of about 280 m agl.

Figure 3-4 shows the vertically integrated tracer concentrations at 4 p.m. The Moss Landing plume is traveling primarily towards the east-northeast, with part of the plume (at about 70 km from the source) heading in a southerly direction. The average height of the plume centerline is about 105 m agl. As in the 8 a.m. and noon results, the Pittsburg plume is more steady in direction, heading towards the east-southeast initially and towards the southeast further downwind, with an average plume centerline height of about 280 m agl.

3.3.2 Plume chemistry – early morning

Figure 3-5 shows the plume centerline concentrations of NO, NO_2, and NO_x downwind of Moss Landing at 8 a.m. The ambient NO concentrations are very low and cannot be distinguished in the plot. The concentrations approach ambient values at about 40 to 50 km from the source. This is also apparent in Figure 3-6, which shows plume centerline concentrations of ozone, nitric acid, and NO_y (NO_x + oxidized products).

As seen in Figure 3-6, plume centerline concentrations of ozone are below the ambient value up to about 50 km from the source, but a small amount of nitric acid in excess of the background is produced in the plume from 5 km to 40 km downwind of the source. Also, we see that ozone concentrations in the plume centerline are zero up to a distance of about 5 km from the source.

Figure 3-7 shows the crosswind plume concentrations at 8 a.m. of NO_x, O_3, and HNO_3 at plume centerline height and a downwind distance of 5 km from Moss Landing. The ambient concentrations at these points are also shown for reference. The plume width is of the order of 6 km. We see that the plume NO_x results in scavenging of ozone at the plume centerline, but a small amount of nitric acid (about 0.1 ppb) is formed at the plume centerline in excess of the background value.

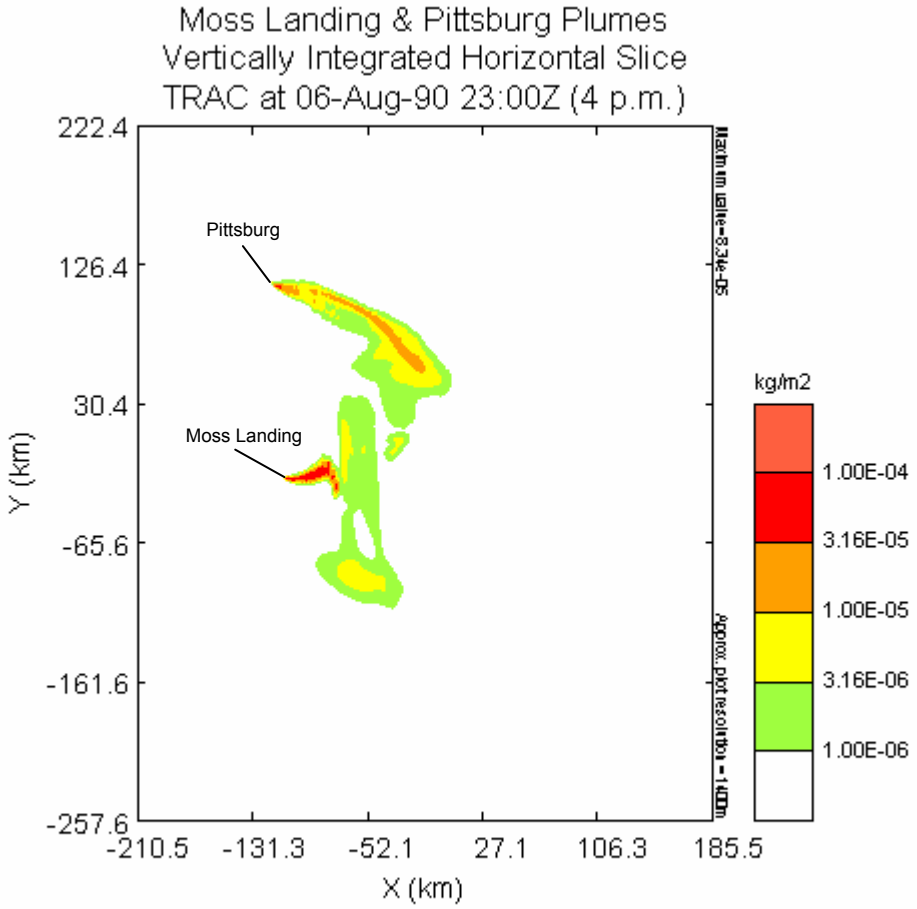

Figure 3-4. Vertically integrated tracer concentrations from the Moss Landing and Pittsburg power plants at 4 p.m. on August 6, 1990.

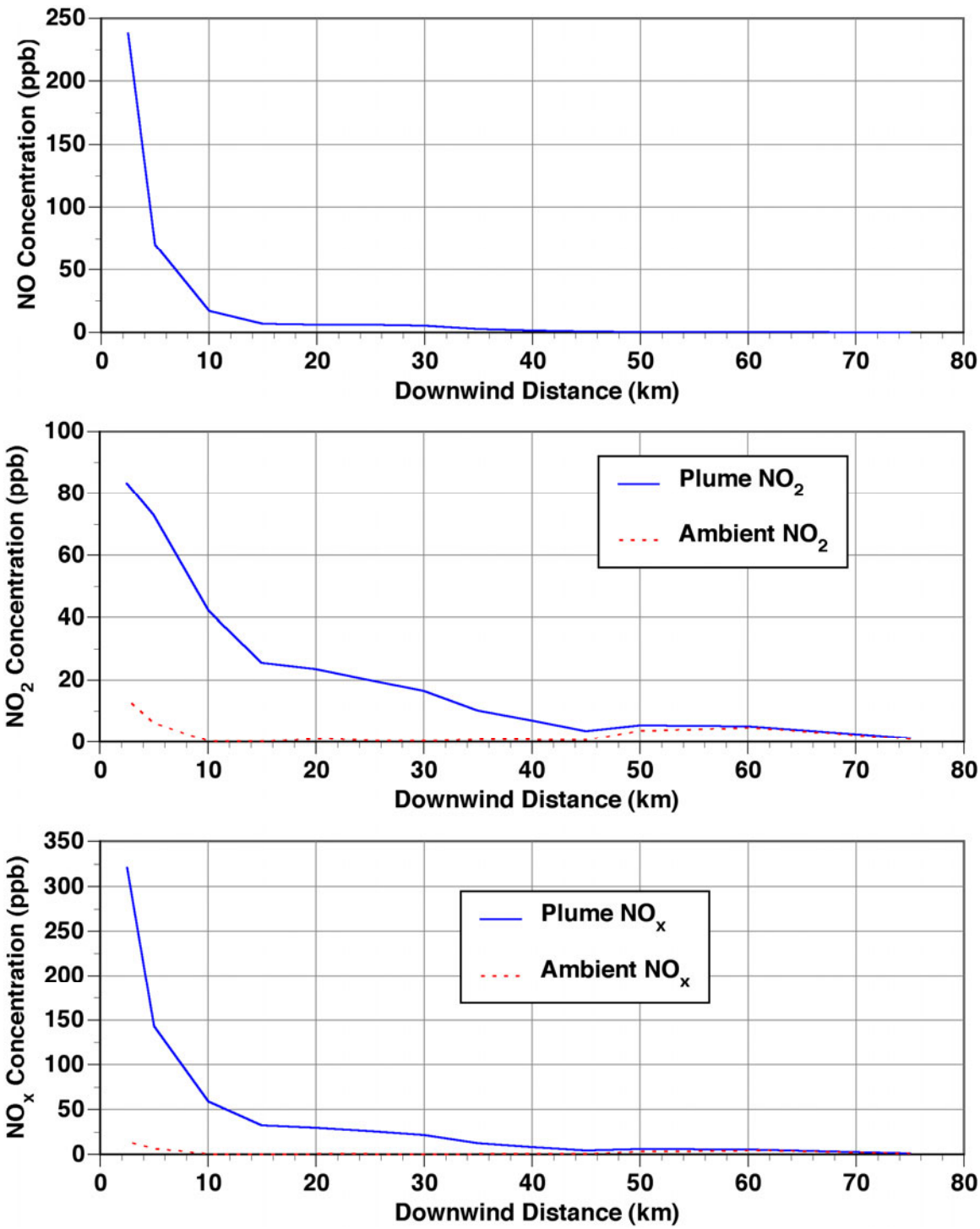

Figure 3-5. Plume centerline concentrations of NO, NO_2, and NO_x downwind of the Moss Landing power plant at 8 a.m. on August 6, 1990.

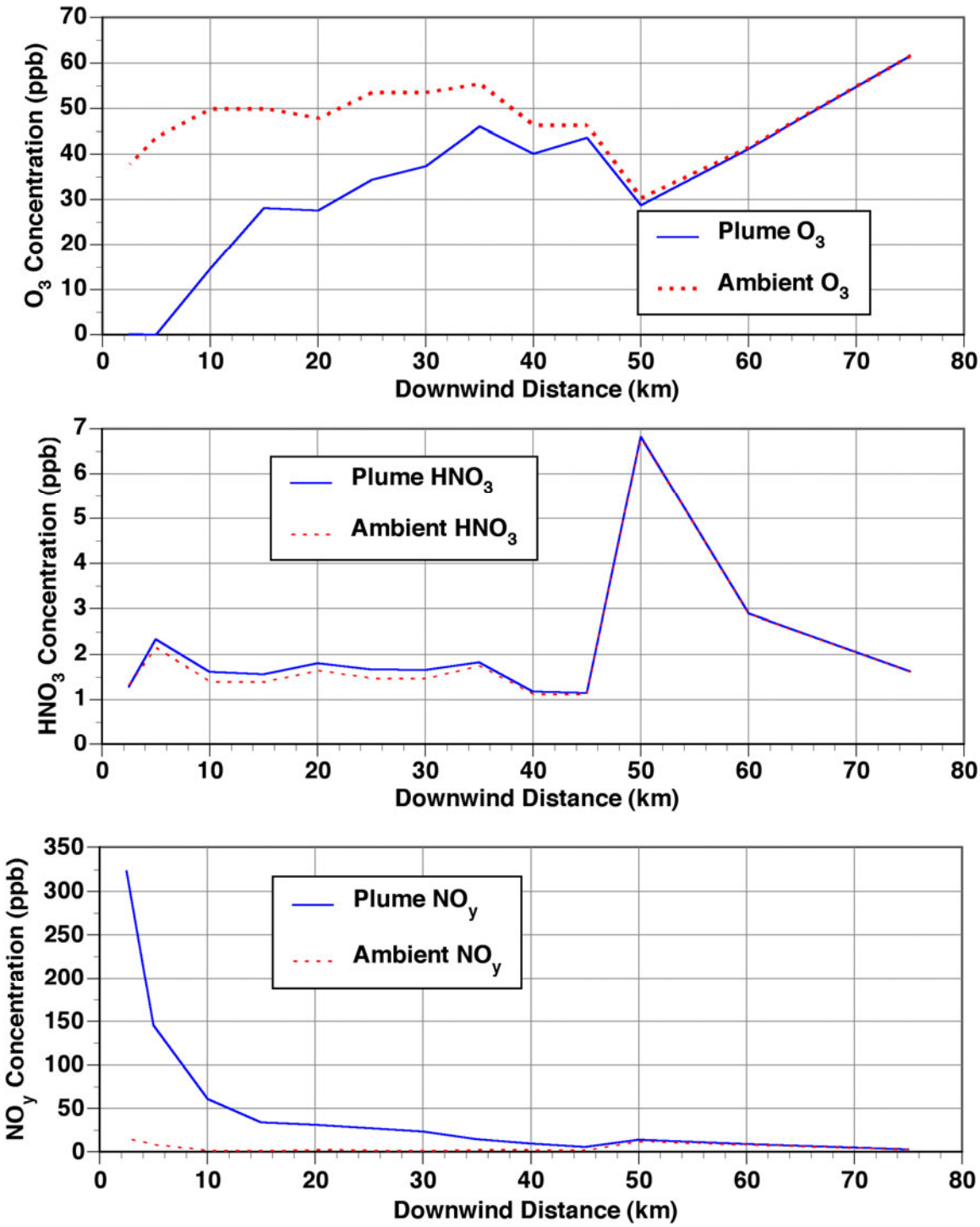

Figure 3-6. Plume centerline concentrations of O_3, HNO_3, and NO_y downwind of the Moss Landing power plant at 8 a.m. on August 6, 1990.

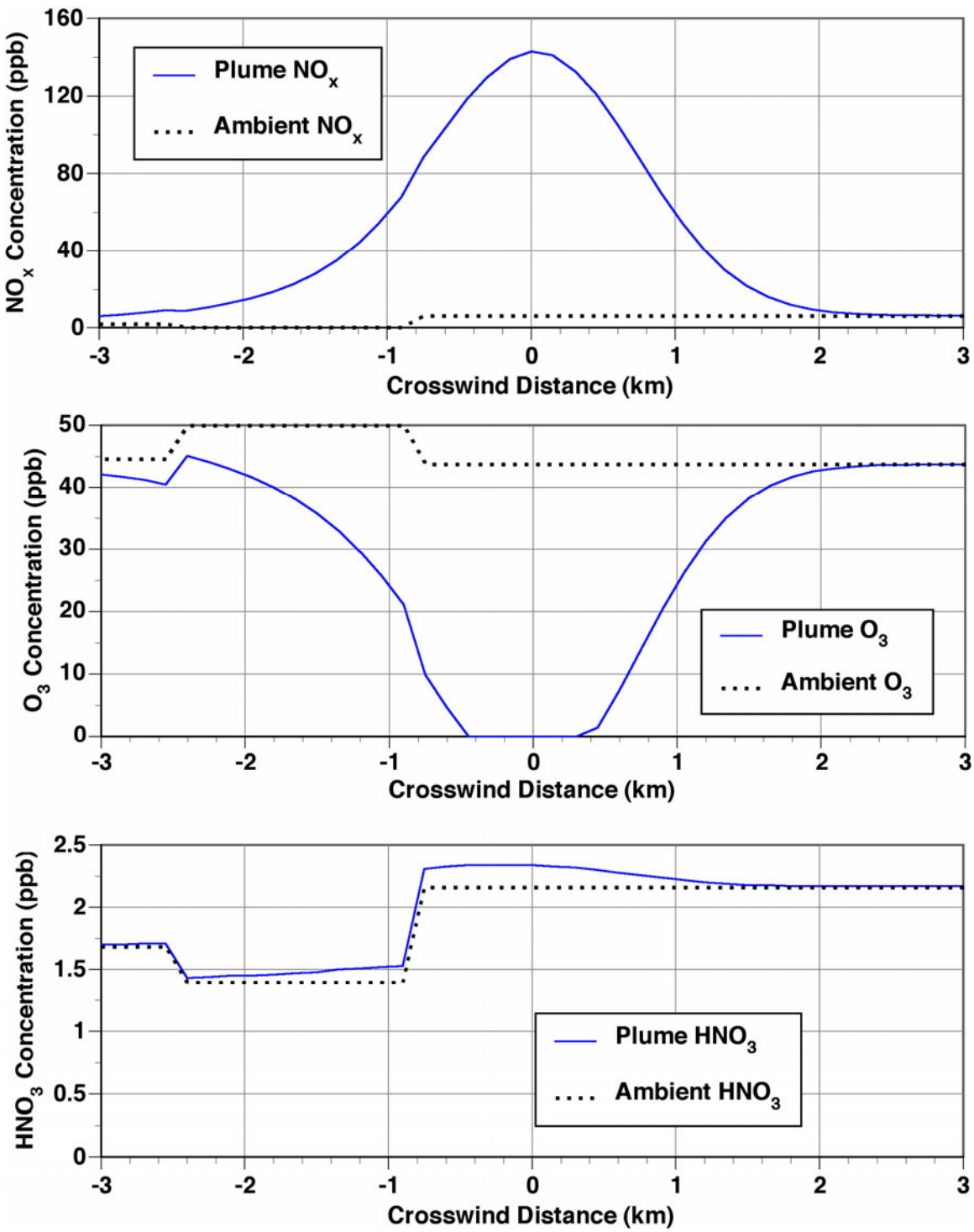

Figure 3-7. Across plume concentrations of NO_x, O_3, and HNO_3 5 km downwind of the Moss Landing power plant at 8 a.m. on August 6, 1990.

At a downwind distance of 25 km (Figure 3-8), the Moss Landing plume width is about 15 km, and the ozone at the plume centerline is depressed from the ambient value by about 15 ppb. We still note a slight production of nitric acid in the plume (about 0.1 ppb over the background value). At 50 km from the source (Figure 3-9), the plume width is of the order of 40 km, and it is harder to distinguish the plume from the background. The NO_x at the plume centerline is in excess of the background value by about 50%, but the plume ozone has recovered to background levels, and there is no excess nitric acid in the plume.

Figure 3-10 shows the plume centerline concentrations of NO, NO_2, and NO_x downwind of Pittsburg at 8 a.m., while Figure 3-11 shows the corresponding concentrations of ozone, nitric acid, and NO_y. In contrast to the Moss Landing plume, there is very little production of nitric acid in the Pittsburg plume, and plume ozone concentrations are below the background value even at a distance of 75 km from the source.

Figure 3-12 shows the crosswind concentrations of NO_x, O_3, and HNO_3 at 8 a.m. in the Pittsburg plume at plume centerline height and a downwind distance of 10 km. As can be seen from Figure 3-12, the Pittsburg plume is considerably narrower than the Moss Landing plume. The plume width is less than 4 km at a downwind distance of 10 km.

Figure 3-13 shows that, at a downwind distance of 25 km, the Pittsburg plume is still quite narrow, with a plume width of about 5 km. The plume NO_x is in excess of the background value at the plume centerline by about 40 ppb, and the ozone at the plume centerline is more than 20 ppb below the background value. A small amount of nitric acid (about 0.1 ppb) is produced at the plume centerline.

At 50 km from the source (Figure 3-14), the Pittsburg plume is still quite narrow, with a plume width of the order of 10 to 15 km. The plume NO_x is about 75% in excess of the background value at the plume centerline, and the plume ozone has almost recovered to background levels. The nitric acid in the plume is indistinguishable from the background.

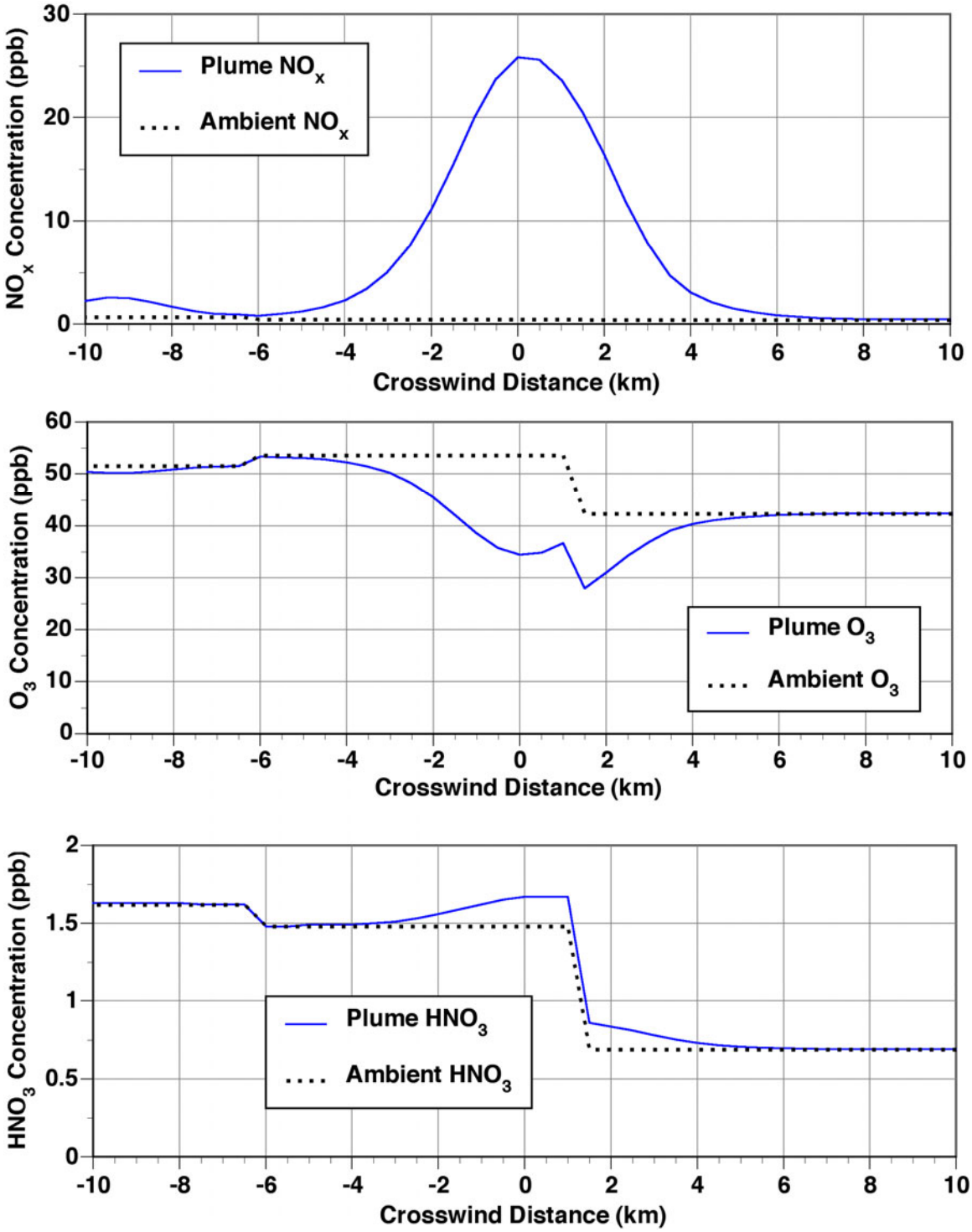

Figure 3-8. Across plume concentrations of NO_x, O_3, and HNO_3 25 km downwind of the Moss Landing power plant at 8 a.m. on August 6, 1990.

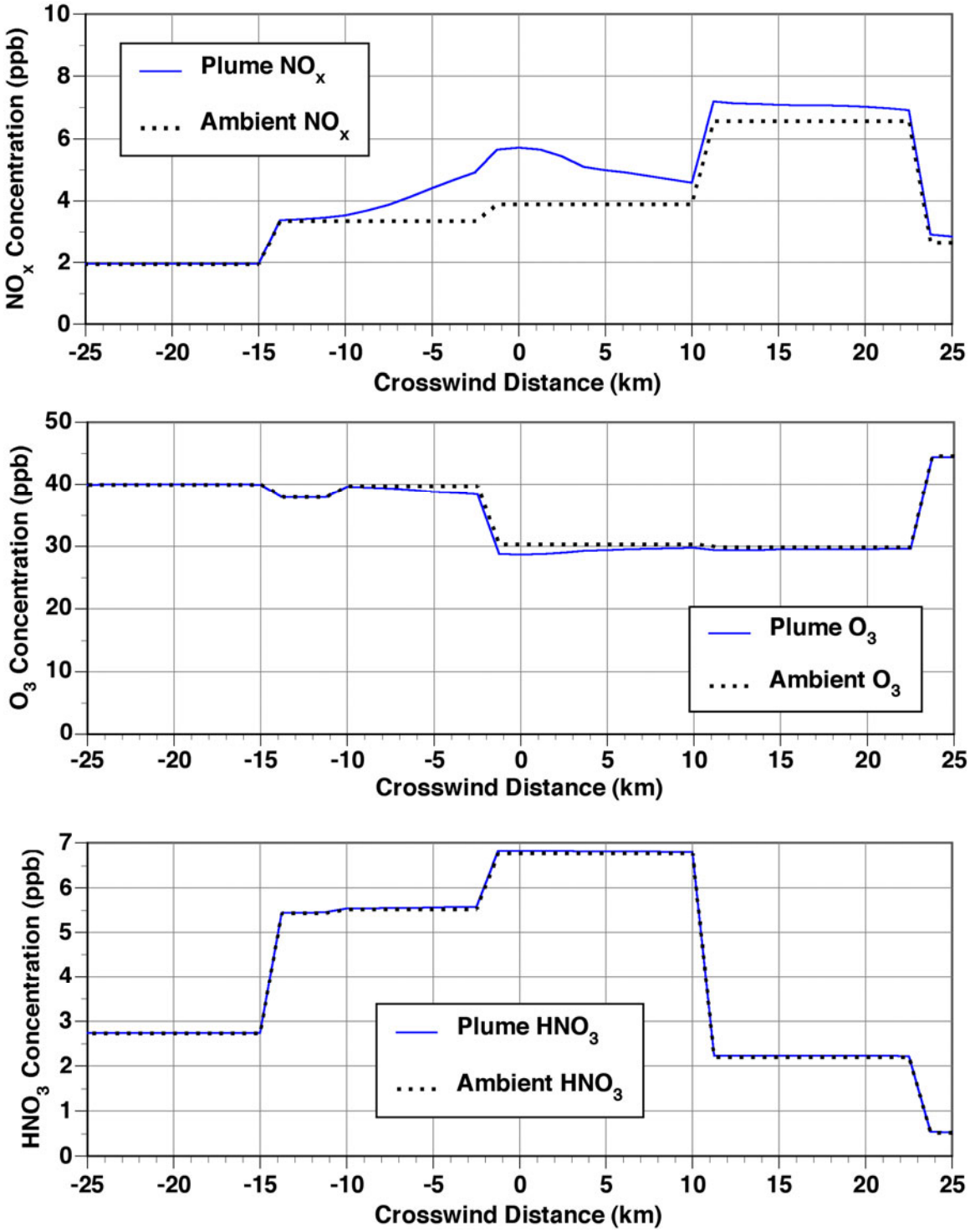

Figure 3-9. Across plume concentrations of NO_x, O_3, and HNO_3 50 km downwind of the Moss Landing power plant at 8 a.m. on August 6, 1990.

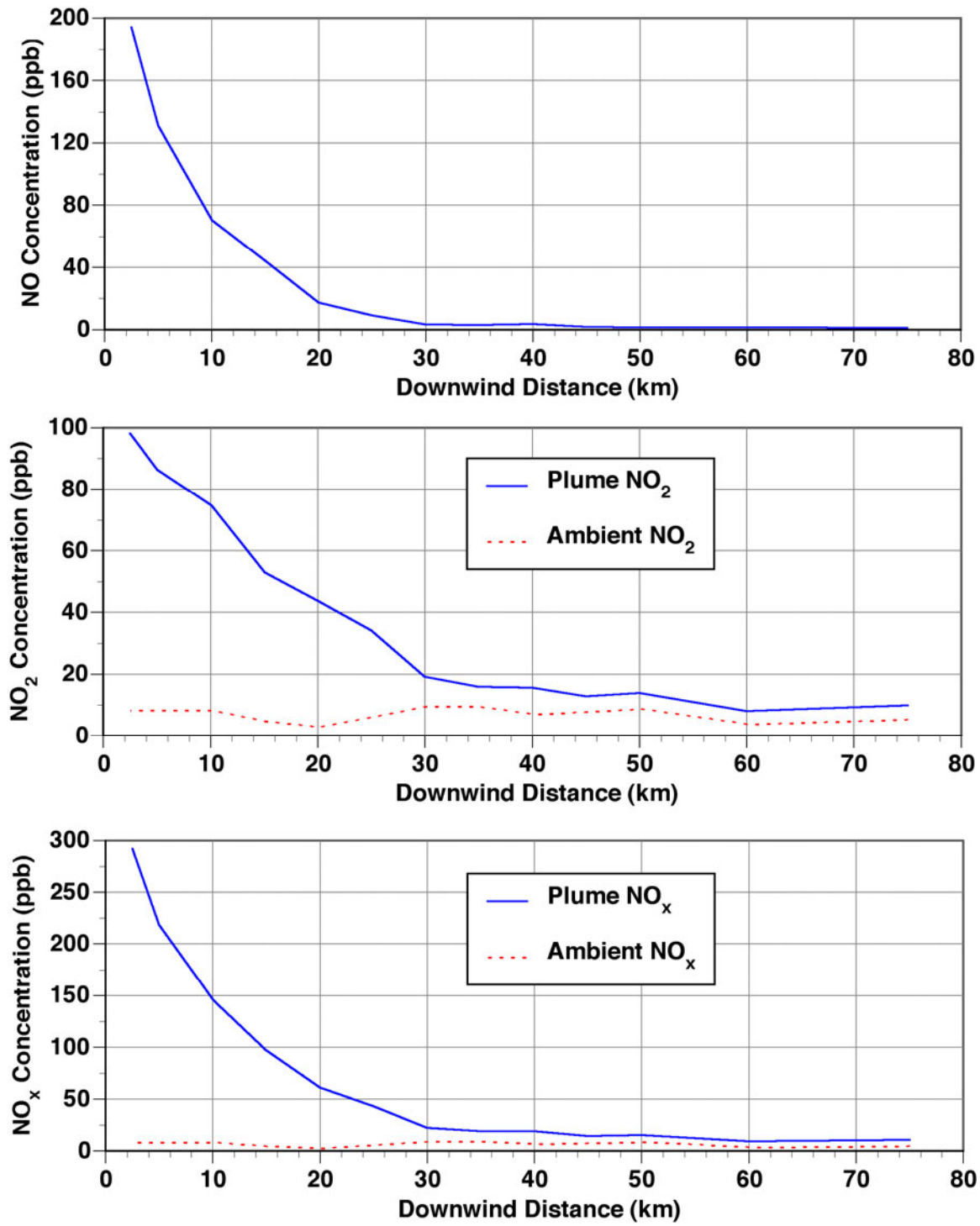

Figure 3-10. Plume centerline concentrations of NO, NO_2, and NO_x downwind of the Pittsburg power plant at 8 a.m. on August 6, 1990.

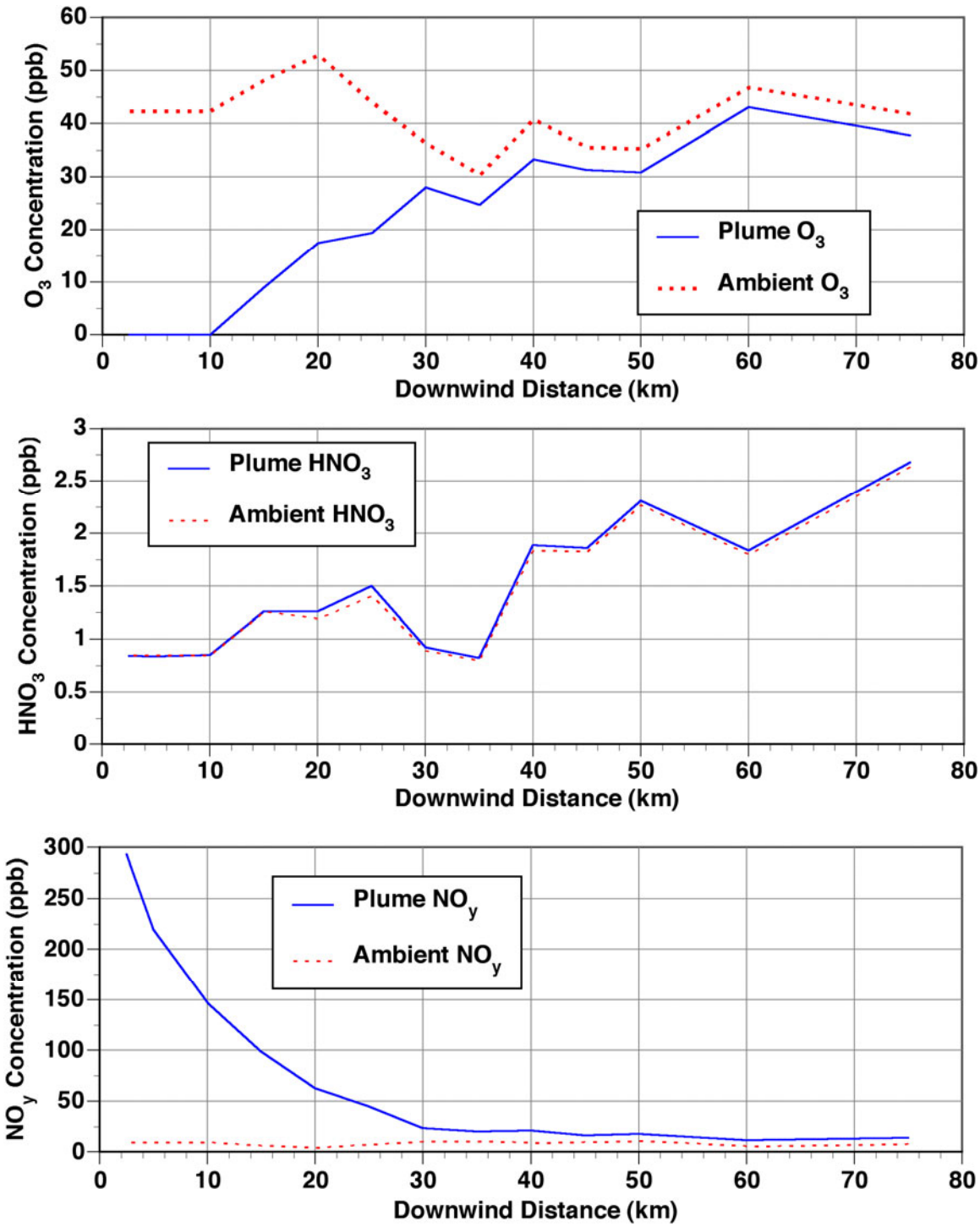

Figure 3-11. Plume centerline concentrations of O_3, HNO_3, and NO_y downwind of the Pittsburg power plant at 8 a.m. on August 6, 1990.

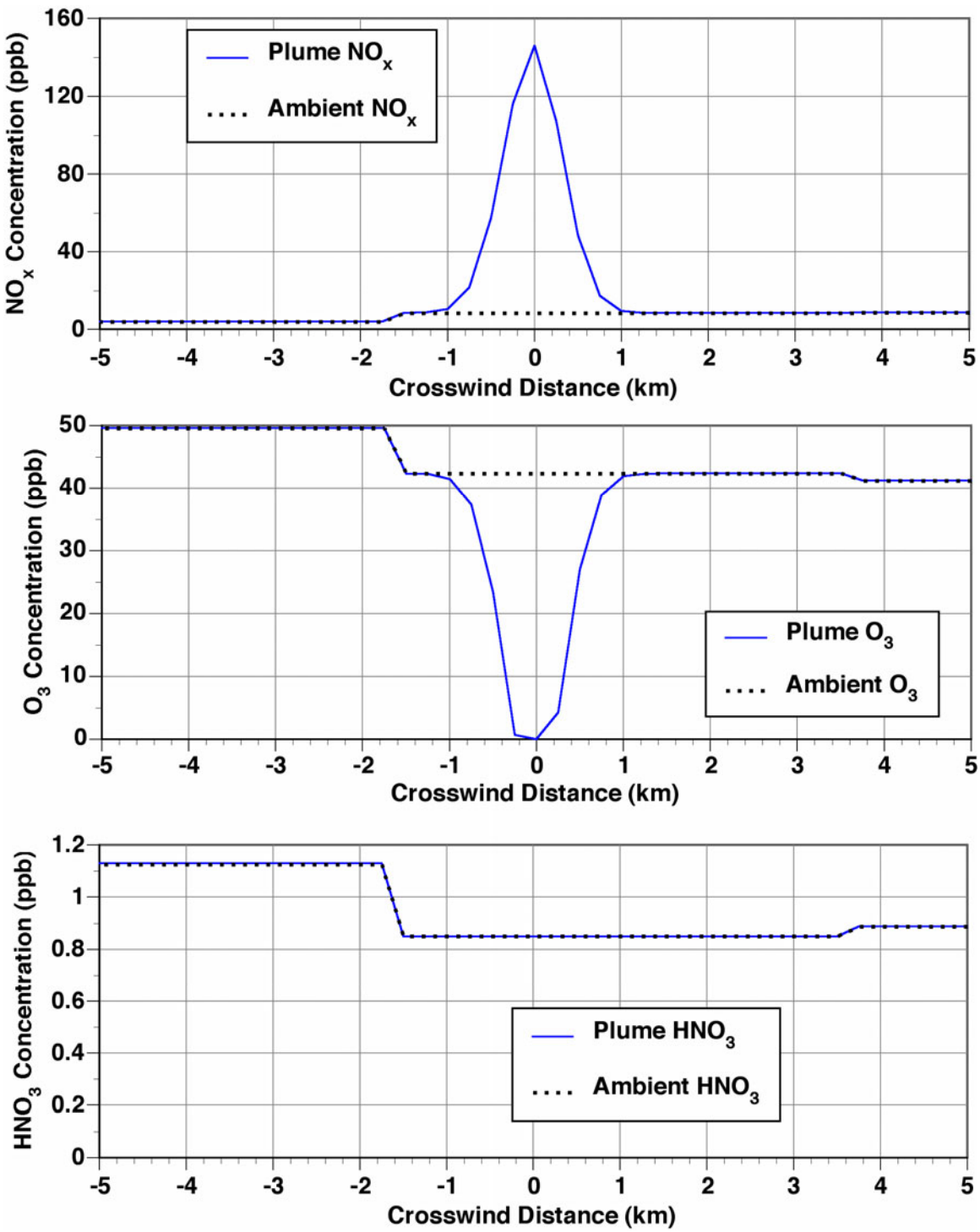

Figure 3-12. Across plume concentrations of NO_x, O_3, and HNO_3 10 km downwind of the Pittsburg power plant at 8 a.m. on August 6, 1990.

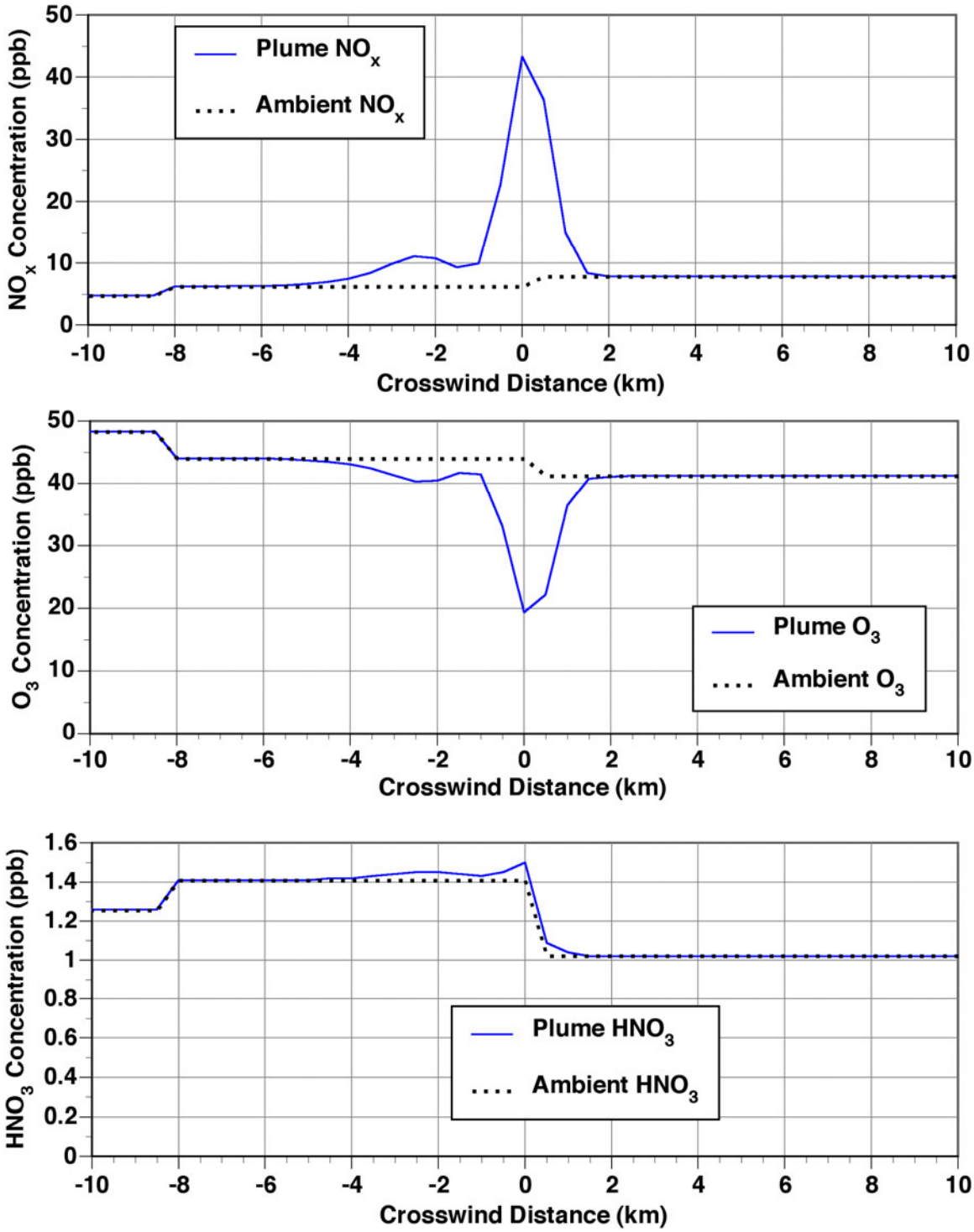

Figure 3-13. Across plume concentrations of NO_x, O_3, and HNO_3 25 km downwind of the Pittsburg power plant at 8 a.m. on August 6, 1990.

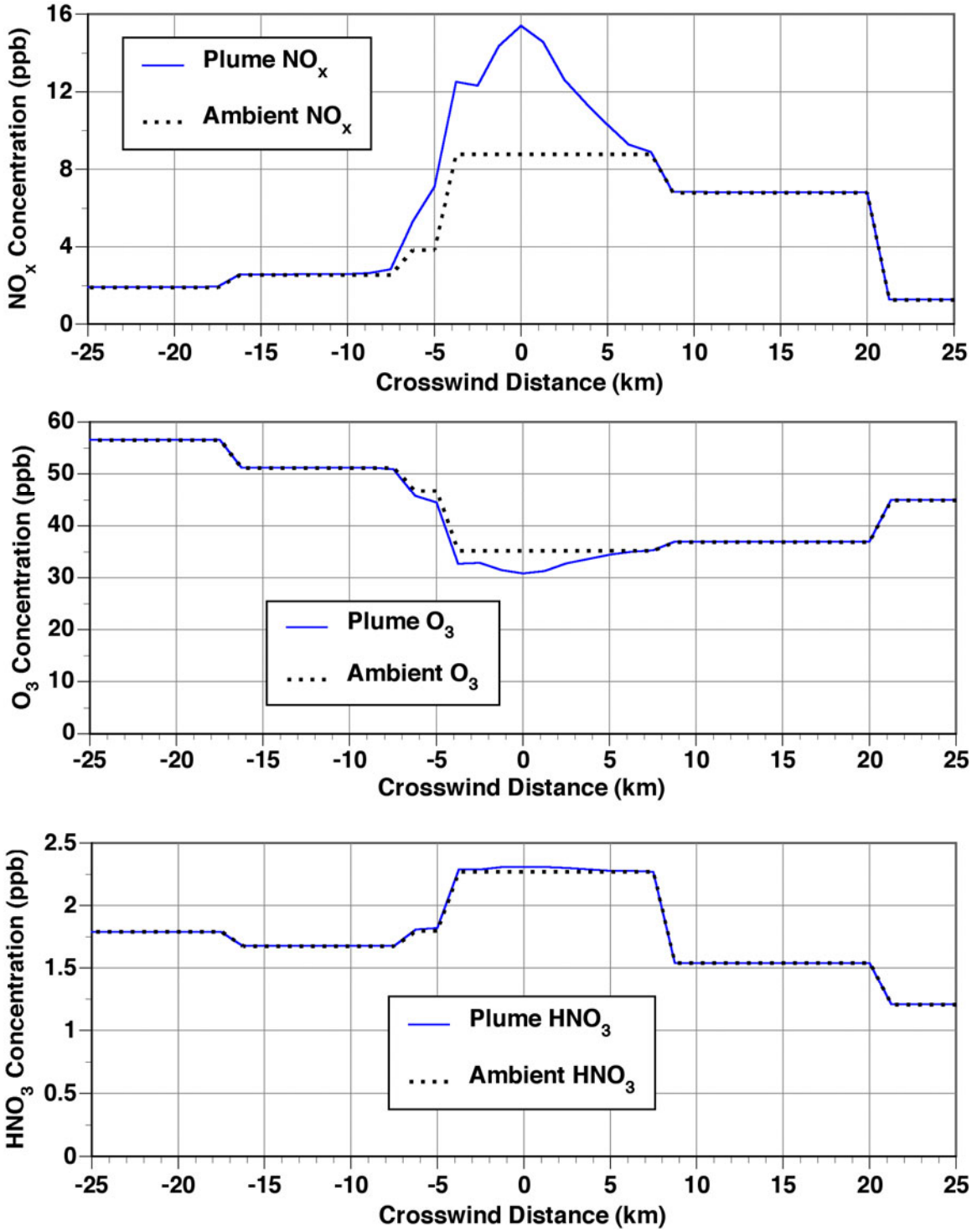

Figure 3-14. Across plume concentrations of NO_x, O_3, and HNO_3 50 km downwind of the Pittsburg power plant at 8 a.m. on August 6, 1990.

3.3.3 Plume chemistry – midday

The downwind results for noon for the Moss Landing plume are shown in Figures 3-15 and 3-16, respectively. Figure 3-15 shows the downwind NO, NO_2 and NO_x concentrations at the plume centerline, while Figure 3-16 shows the ozone, nitric acid and NO_y concentrations. We see from Figure 3-16 that the ozone in the plume centerline is almost completely scavenged to a distance of about 35 km, but recovers rapidly to background levels further downwind. We also see a significant amount of nitric acid production in the plume, with a peak at about 35 km, where the HNO_3 at the plume centerline is in excess of the background value of 2 ppb by more than 5 ppb.

Figure 3-17 shows the plume traverse (crosswind) results for the Moss Landing plume at noon at 10 km downwind of the source. We see that the plume is quite narrow, as compared to the 8 a.m. plume, and that the ozone at the plume centerline is about 40 ppb below the background value. About 0.5 ppb of nitric acid in excess of the background value is produced at the plume centerline.

At 25 km downwind of Moss Landing (Figure 3-18), the plume width is of the order of 10 km at noon, the ozone at the plume centerline is about 35 ppb below the background value, and the plume centerline nitric acid concentrations are almost 3 times the background value of 1 ppb. Figure 3-19 shows that, at a downwind distance of 50 km, the Moss Landing plume is about 30 km wide, the ozone at the plume centerline has almost recovered to background levels, and the nitric acid concentration at the plume centerline exceeds the background value of 2.25 ppb by slightly more than 0.75 ppb.

Figures 3-20 and 3-21 show the downwind results for the Pittsburg plume at noon. We see from Figure 3-21 that the ozone at the plume centerline is about 40 ppb lower than the ambient value up to a downwind distance of about 20 km. Further downwind, the ozone in the plume begins to recover to background levels but is always lower than the background value, even at 75 km downwind, where the plume centerline ozone concentration is about 5 ppb less than the ambient value. The excess nitric acid at the plume centerline is about 0.3 to 0.4 ppb up to a downwind distance of 50 km, and then decreases to 0.2 ppb and lower further downwind.

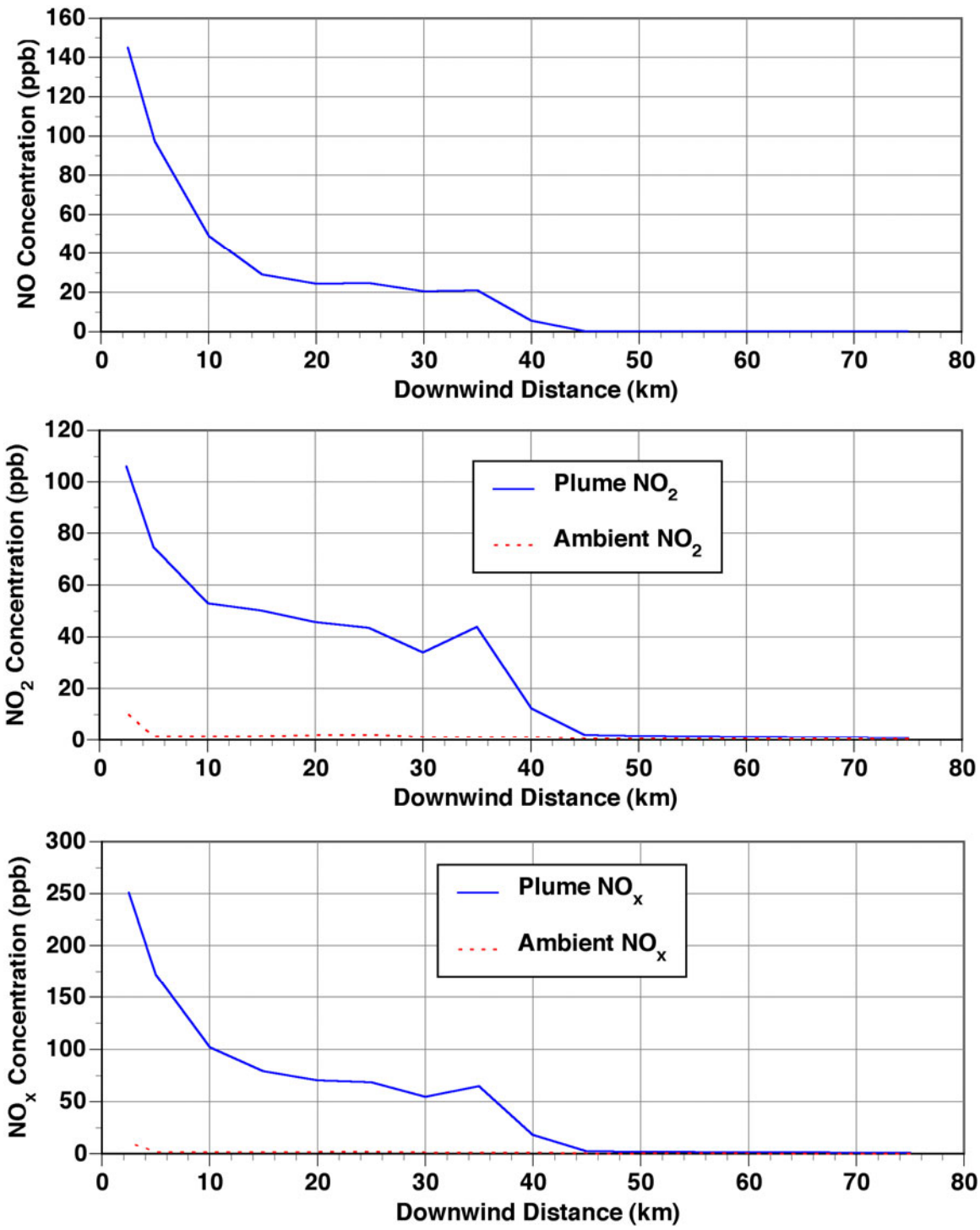

Figure 3-15. Plume centerline concentrations of NO, NO_2, and NO_x downwind of the Moss Landing power plant at 12 noon on August 6, 1990.

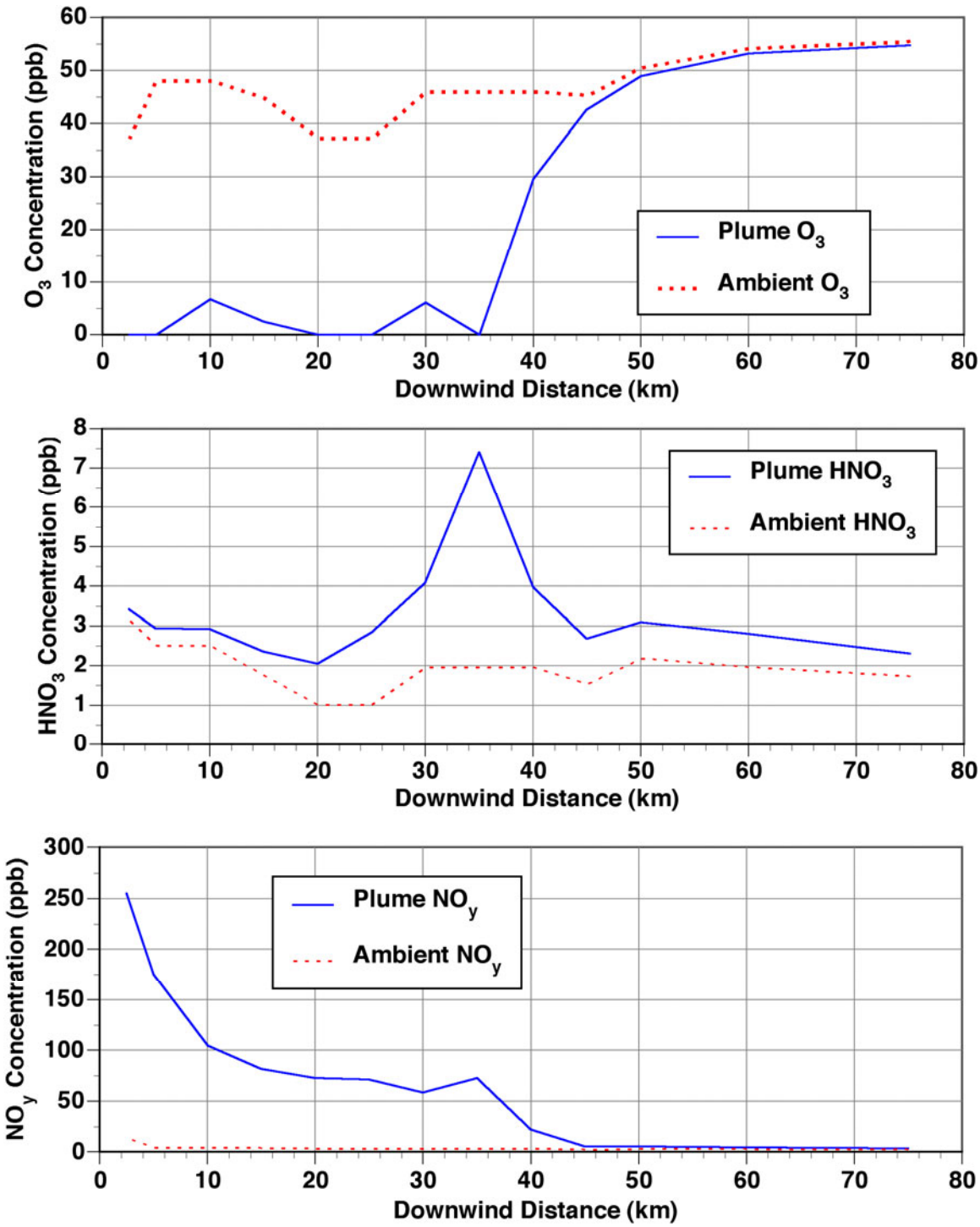

Figure 3-16. Plume centerline concentrations of O_3, HNO_3, and NO_y downwind of the Moss Landing power plant at 12 noon on August 6, 1990.

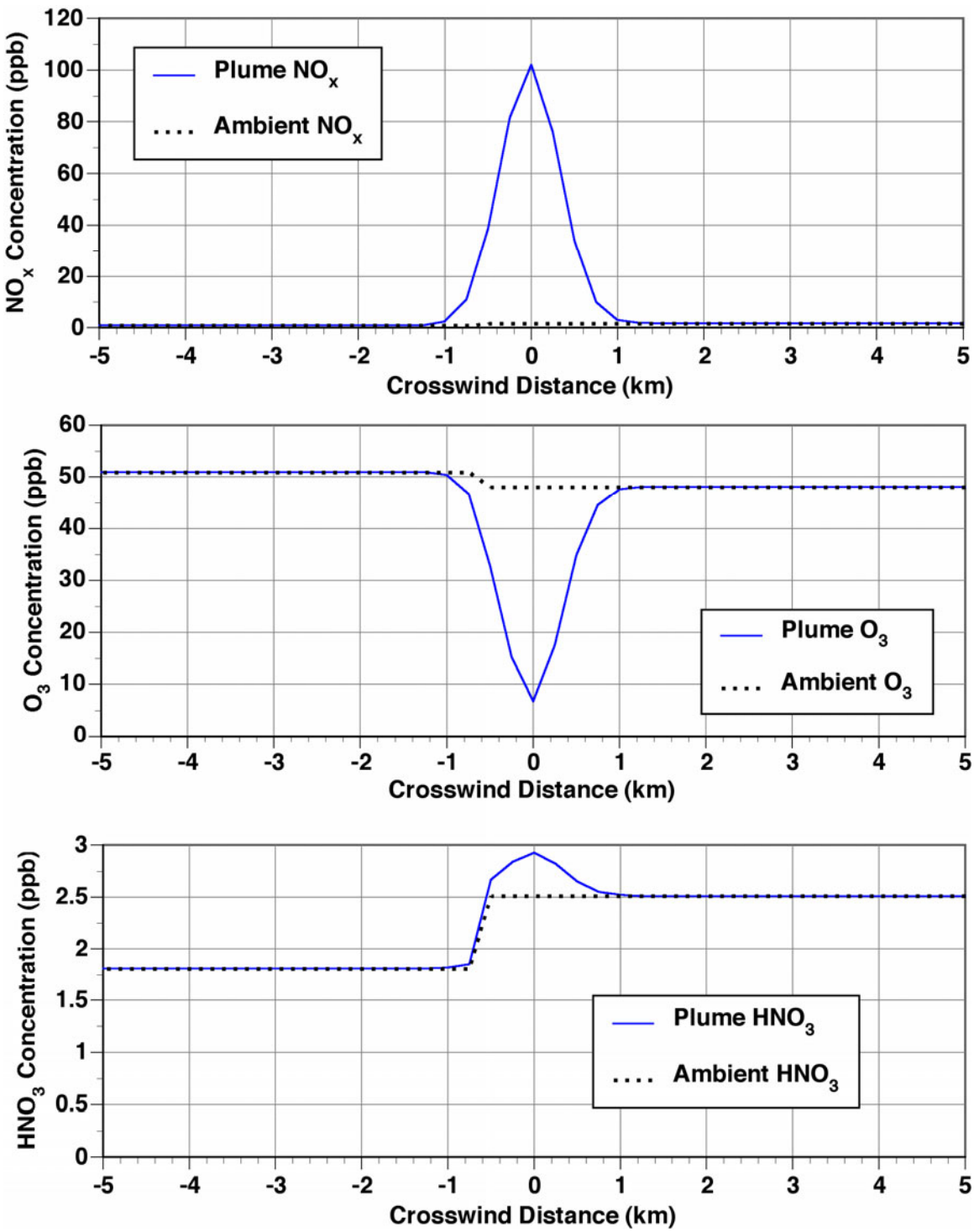

Figure 3-17. Across plume concentrations of NO_x, O_3, and HNO_3 10 km downwind of the Moss Landing power plant at 12 p.m. on August 6, 1990.

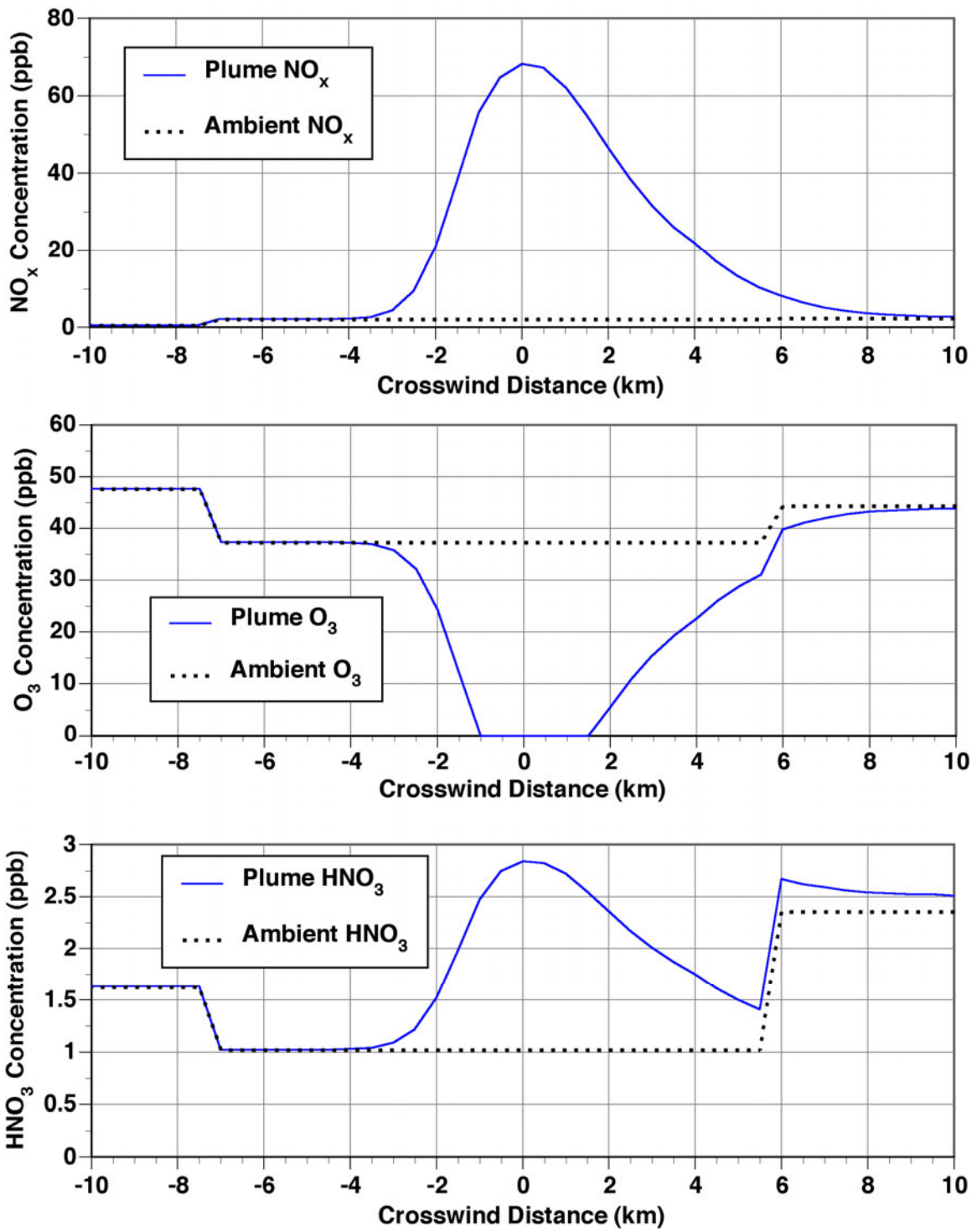

Figure 3-18. Across plume concentrations of NO_x, O_3, and HNO_3 25 km downwind of the Moss Landing power plant at 12 noon on August 6, 1990.

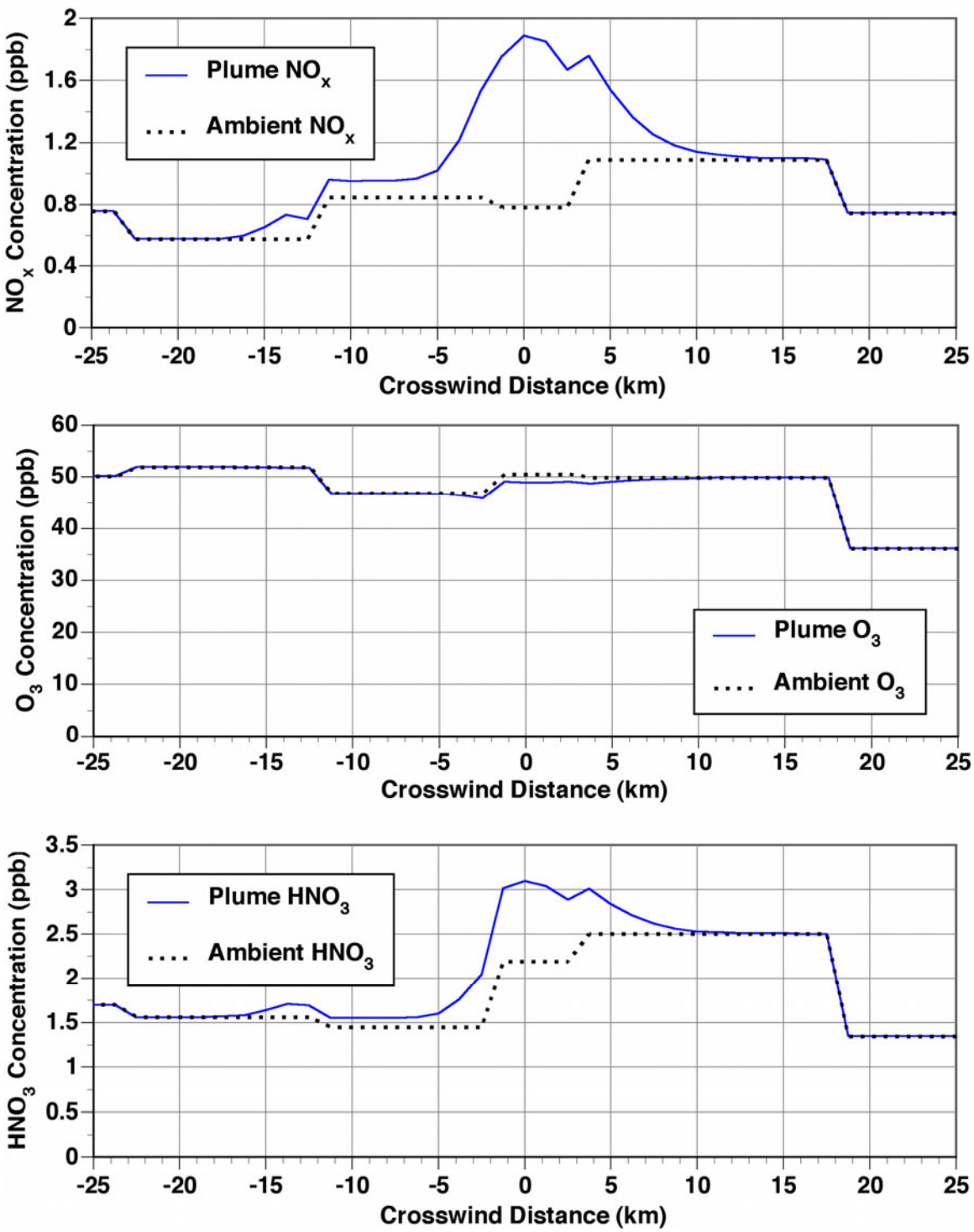

Figure 3-19. Across plume concentrations of NO_x, O_3, and HNO_3 50 km downwind of the Moss Landing power plant at 12 noon on August 6, 1990.

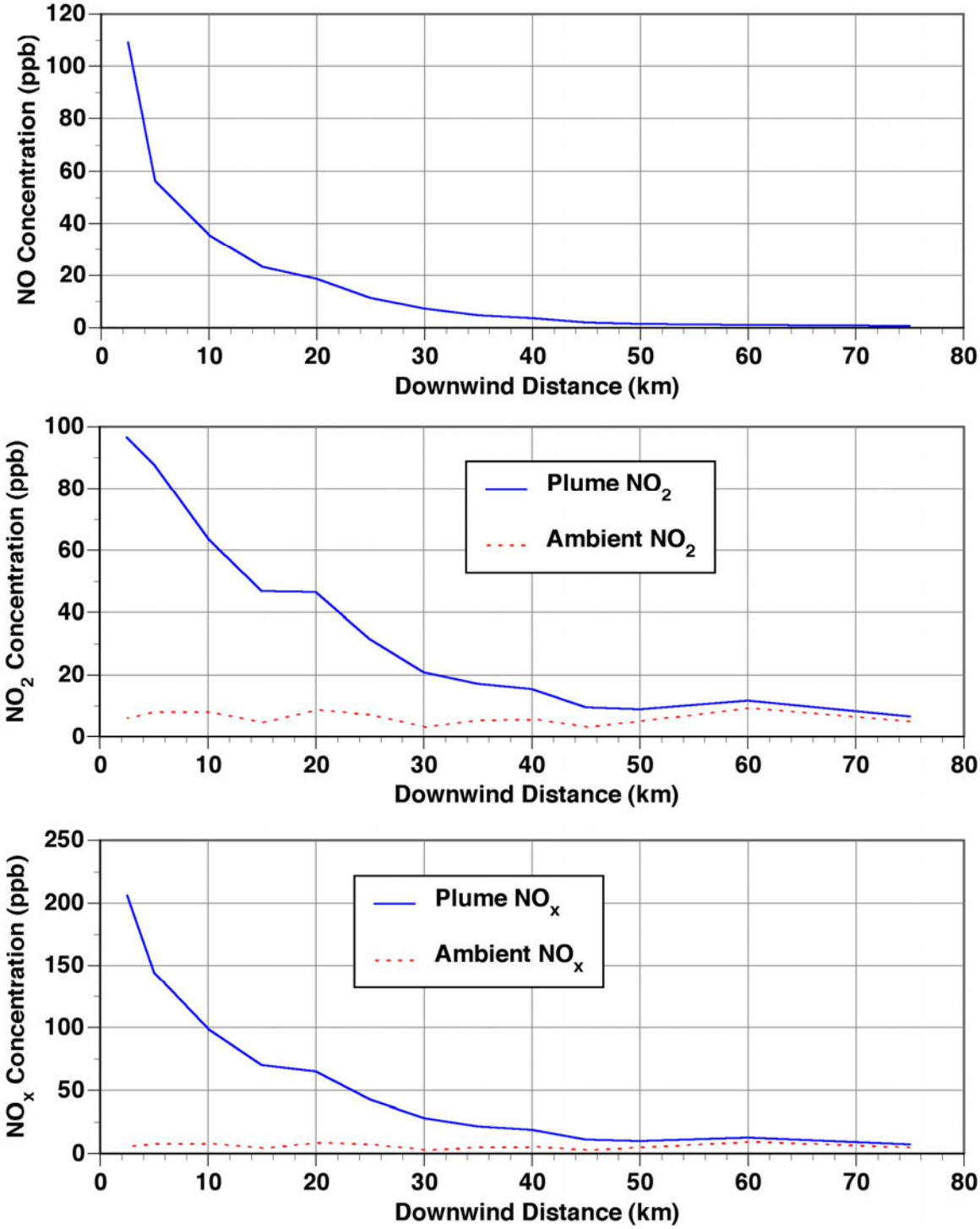

Figure 3-20. Plume centerline concentrations of NO, NO_2, and NO_x downwind of the Pittsburg power plant at 12 noon on August 6, 1990.

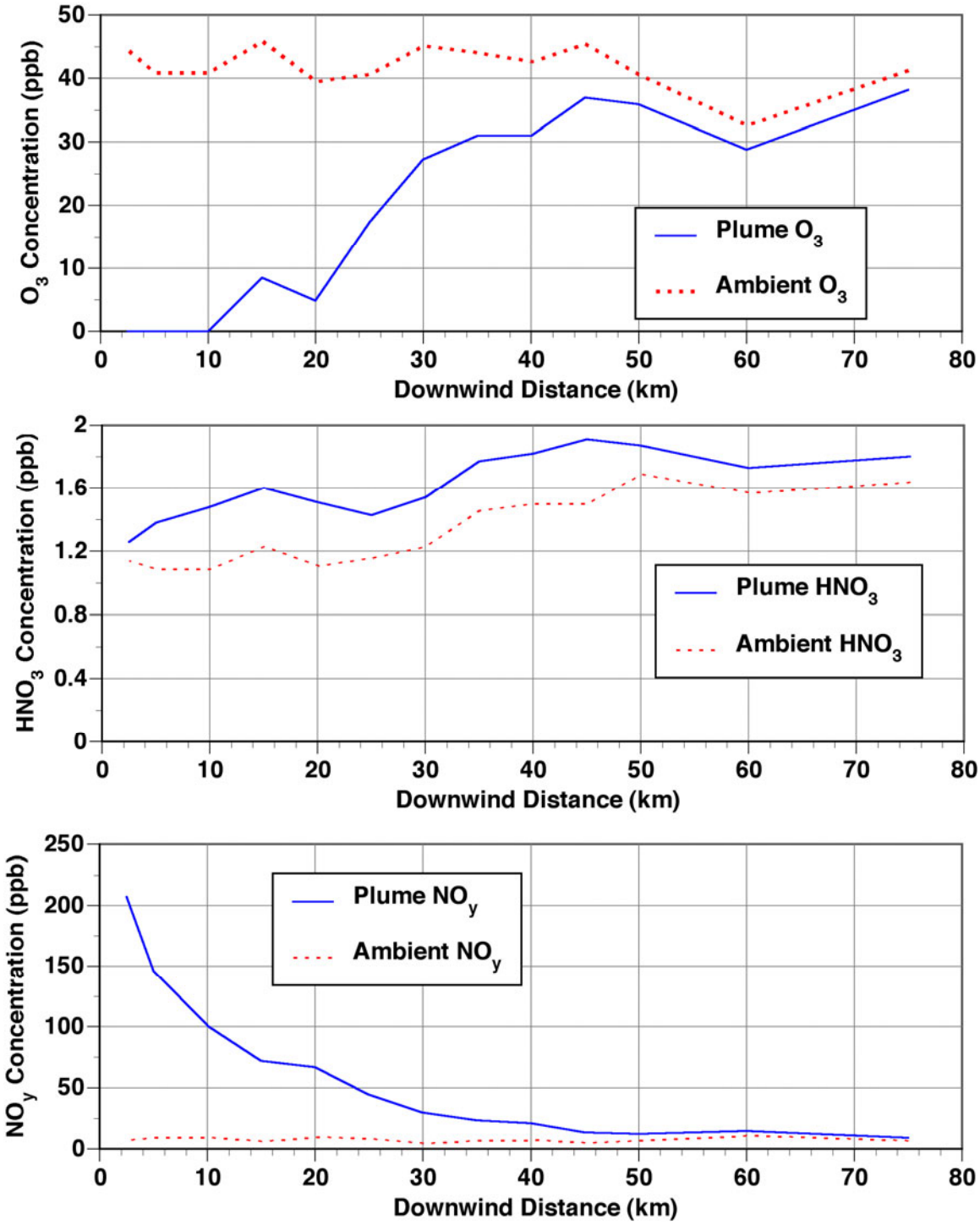

Figure 3-21. Plume centerline concentrations of O_3, HNO_3, and NO_y downwind of the Pittsburg power plant at 12 noon on August 6, 1990.

Figure 3-22 shows the noontime crosswind Pittsburg plume concentrations of NOx, O_3, and HNO_3 at plume centerline height and a downwind distance of 10 km. We see that, at the plume centerline, ozone concentrations are about 40 ppb lower than the ambient value, and that about 0.4 ppb of nitric acid in excess of the background value is produced. The plume width at this downwind distance is of the order of 2 km. The crosswind results for a downwind distance of 25 km are shown in Figure 3-23. The plume width at this distance is about 5 km, and ozone concentrations at the plume centerline are about 20 ppb lower than the background value. About 0.2 ppb of excess nitric acid is produced at the plume centerline.

At 75 km downwind, the Pittsburg plume is less discernible (see Figure 3-24). The nitric acid at plume centerline exceeds the background value by about 0.1 ppb, while the centerline ozone concentration deficit is less than 2 ppb. The plume width is only about 15 to 20 km at this distance.

3.3.4 Plume chemistry - afternoon

Finally, we present the base case results for 4 p.m. on August 6, 1990. Figures 3-25 and 3-26 show the plume centerline downwind results for the Moss Landing plume at 4 p.m. Figure 3-26 shows a rapid recovery of ozone in the plume after a downwind distance of about 20 km. At 45 km downwind, the ozone concentration reaches the background value. After about 50 km downwind, we see some small production of ozone in the plume, leading to an excess of ozone of about 2 to 3 ppb in the plume above the background value to downwind distances of 75 km. The nitric acid at the plume centerline is always in excess of the background value by as much as 2 ppb.

Figures 3-27 shows the 4 p.m. crosswind plume concentrations in the Moss Landing plume at a downwind distance of 10 km. The plume width is approximately 2 km, and the ozone at the plume centerline is completely depleted from the ambient value of 40 ppb. About 0.5 ppb of nitric acid is produced at the plume centerline in excess of the background value.

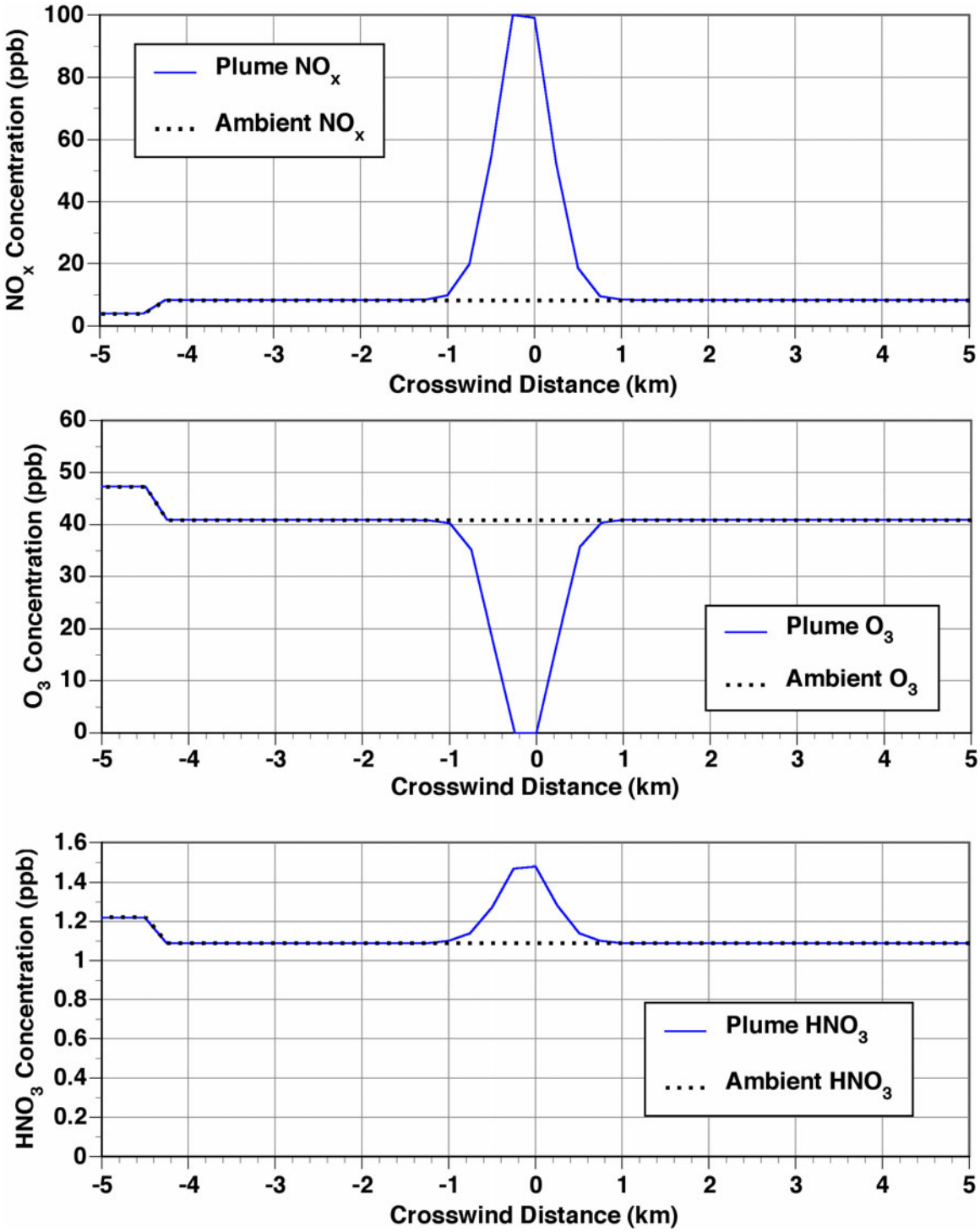

Figure 3-22. Across plume concentrations of NO_x, O_3, and HNO_3 10 km downwind of the Pittsburg power plant at 12 noon on August 6, 1990.

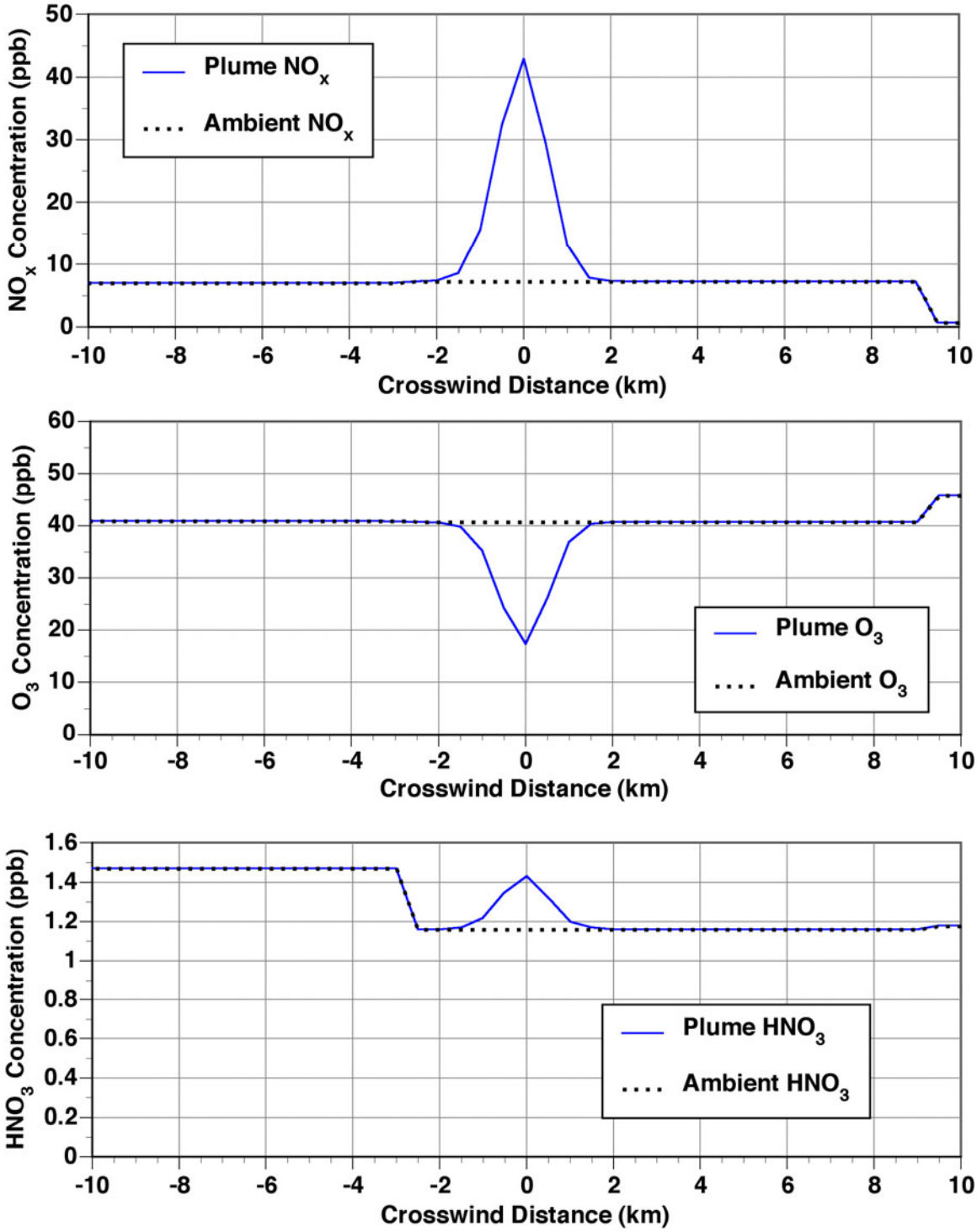

Figure 3-23. Across plume concentrations of NO_x, O_3, and HNO_3 25 km downwind of the Pittsburg power plant at 12 noon on August 6, 1990.

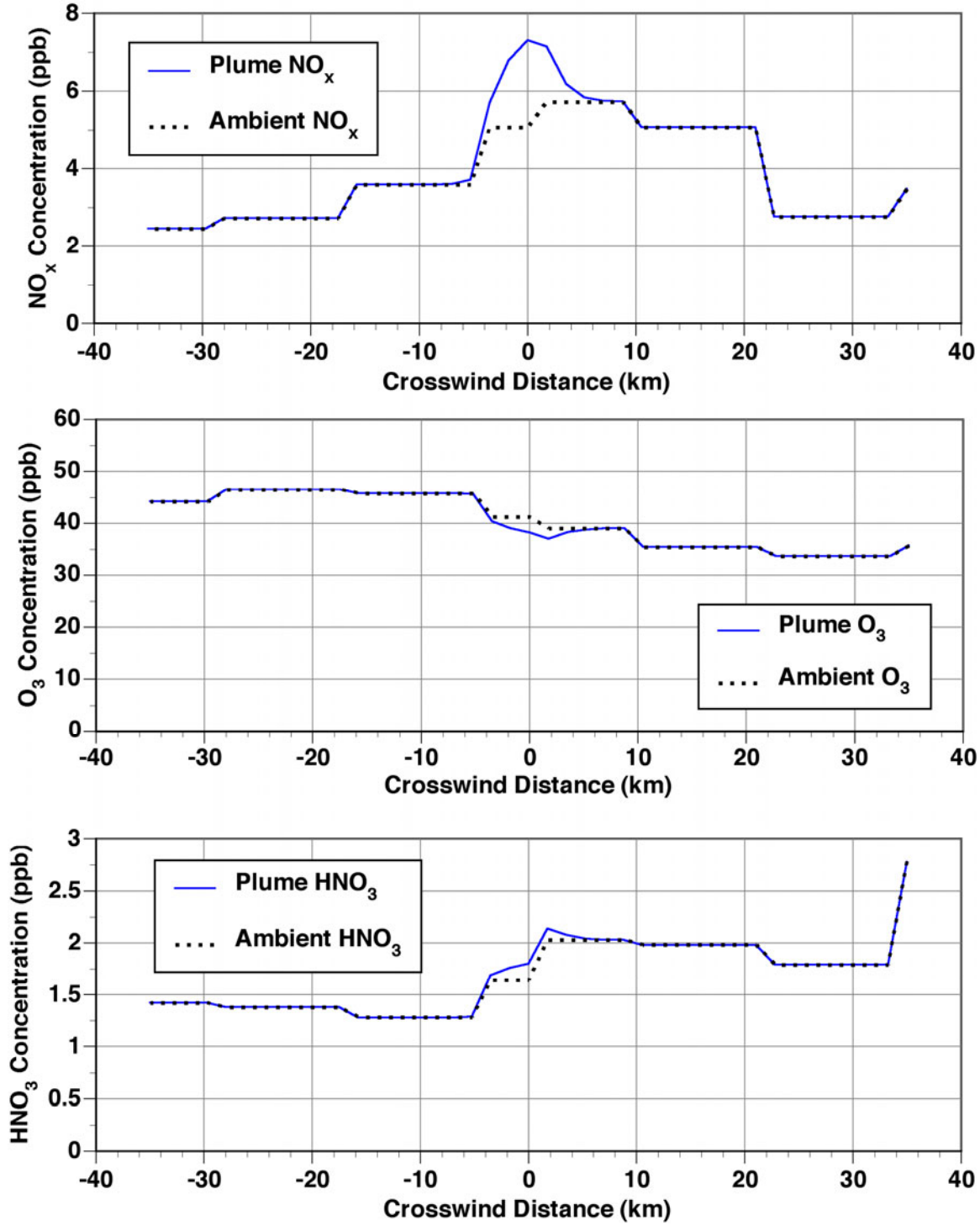

Figure 3-24. Across plume concentrations of NO_x, O_3, and HNO_3 75 km downwind of the Pittsburg power plant at 12 noon on August 6, 1990.

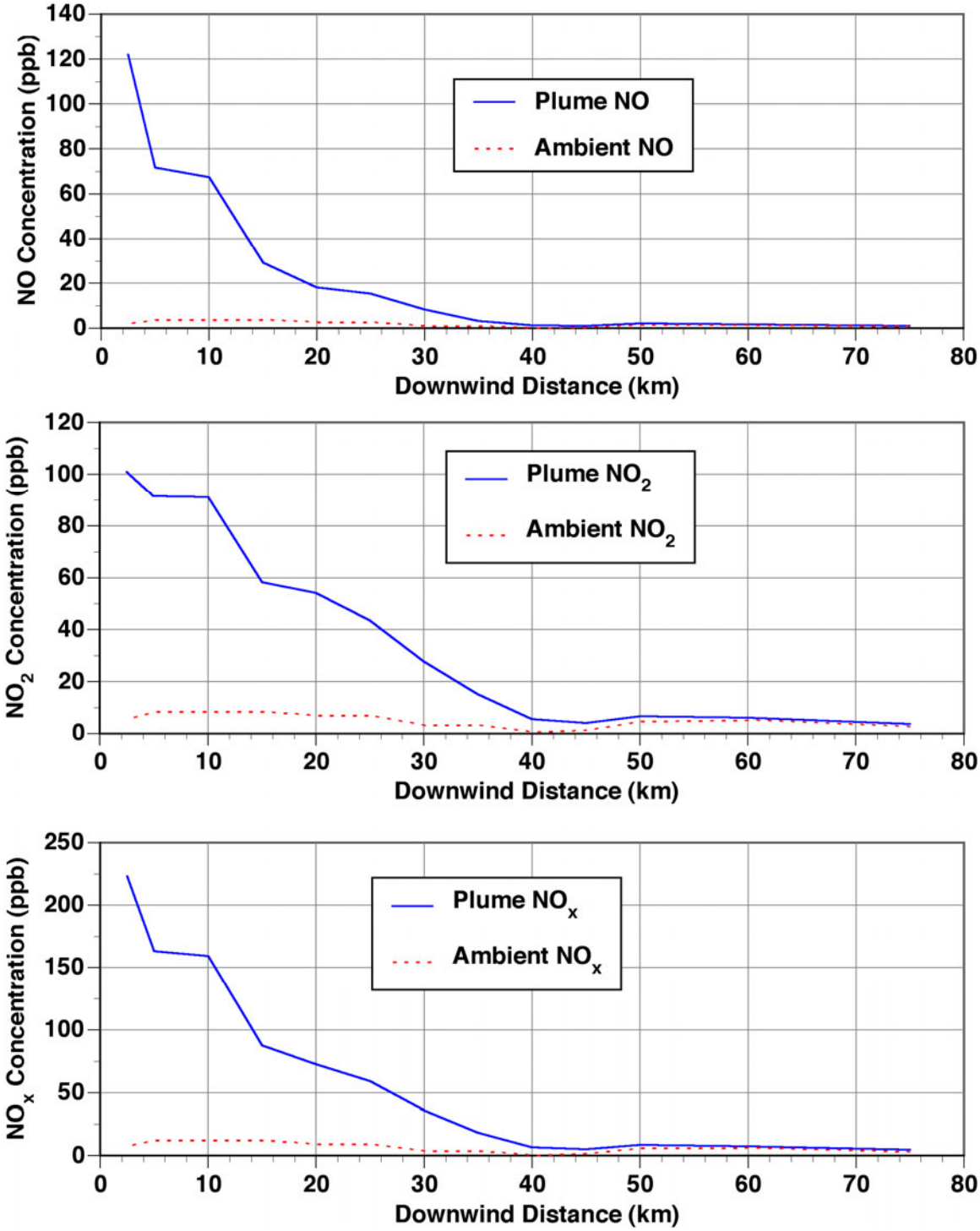

Figure 3-25. Plume centerline concentrations of NO, NO_2, and NO_x downwind of the Moss Landing power plant at 4 p.m. on August 6, 1990.

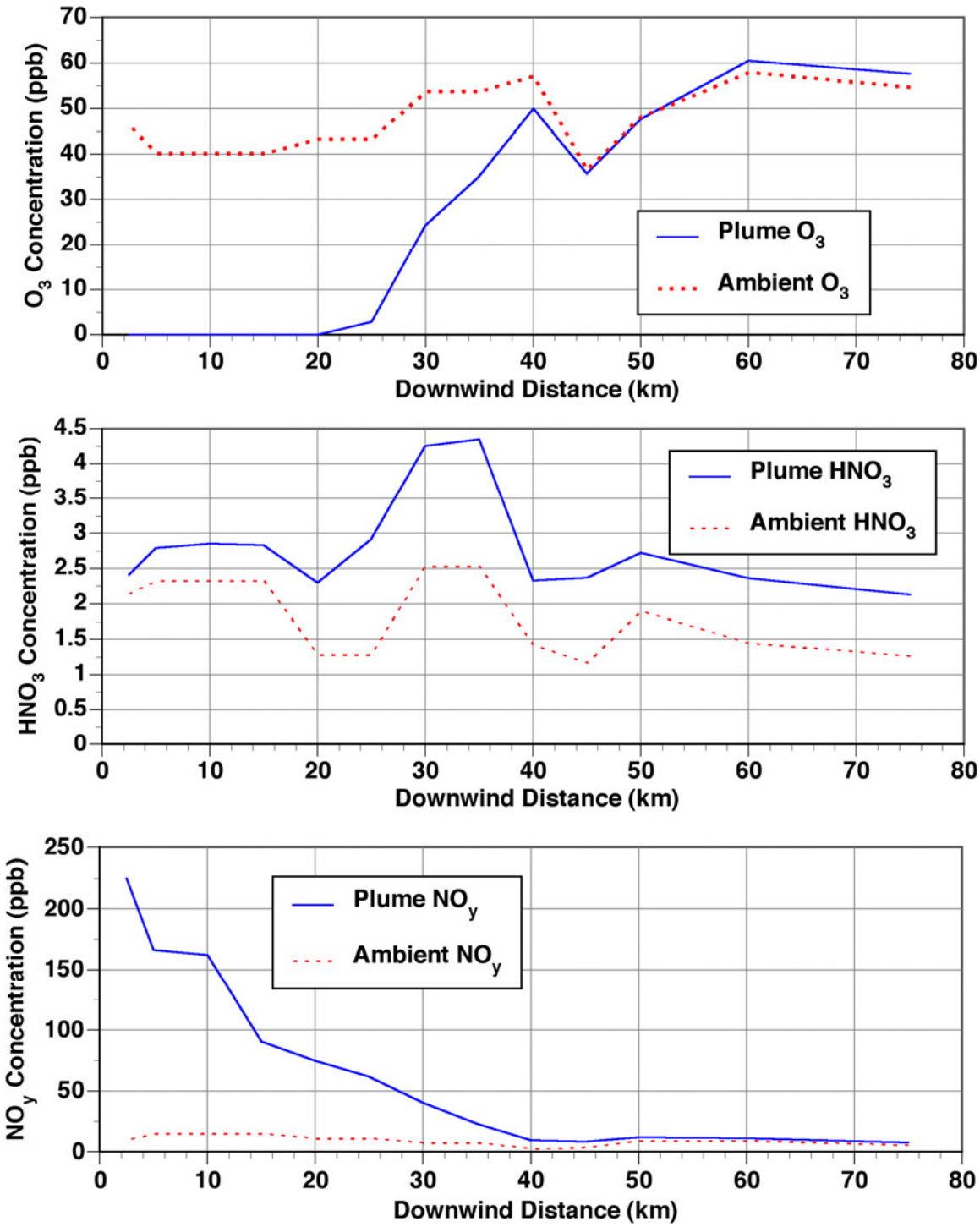

Figure 3-26. Plume centerline concentrations of O_3, HNO_3, and NO_y downwind of the Moss Landing power plant at 4 p.m. on August 6, 1990.

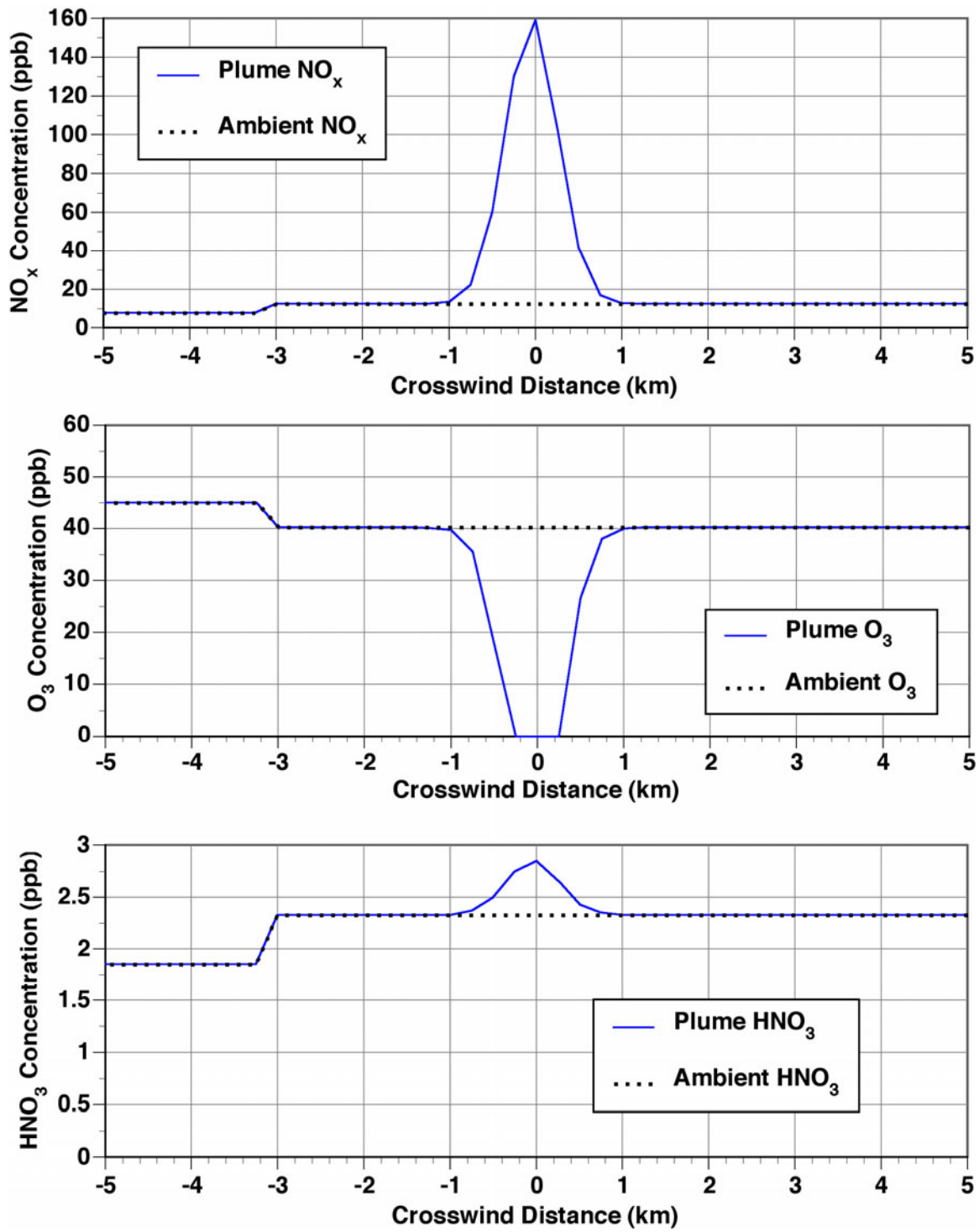

Figure 3-27. Across plume concentrations of NO_x, O_3, and HNO_3 10 km downwind of the Moss Landing power plant at 4 p.m. on August 6, 1990.

At a downwind distance of 25 km, Figure 3-28 shows that there is still some ozone depletion in the Moss Landing plume centerline, but the plume is producing a significant amount of nitric acid (about 1.75 ppb in excess of the background value of 1.25 ppb at the plume centerline). The plume width at this distance is about 12 to 15 km. Figure 3-29 shows that further downwind, at a distance of 75 km, the plume width is about 20 to 25 km, and there is some production of ozone at the plume centerline of about 3 ppb over the background value. The excess nitric acid at the plume centerline is slightly less than 1 ppb over the background value of 1.25 ppb.

The downwind results for the Pittsburg plume centerline concentrations at 4 p.m. are shown in Figures 3-30 and 3-31. As in the previous results for the Pittsburg plume, we see that the plume centerline ozone concentrations are always lower than the background value, but there is significant nitric acid production in the plume, with a maximum of about 1 ppb over the background value at 50 km from the source.

Figure 3-32 shows the crosswind concentration profiles at 4 p.m. for the Pittsburg plume at a downwind distance of 10 km. The width of the plume is approximately 2 km, and the ozone deficit at the plume centerline is about 35 ppb. Nitric acid concentrations at the plume centerline are about 0.25 ppb higher than the background value. At a downwind distance of 25 km (Figure 3-33), the plume width is about 4 km, and the ozone at the plume centerline is lower than the background value by about 20 ppb. The plume centerline nitric acid concentration is about 0.5 ppb higher than the ambient value.

At 75 km downwind (Figure 3-34), the width of the Pittsburg plume is less than 20 km, and the ozone concentration at the plume centerline is about 12 ppb lower than the ambient concentration, while the nitric acid concentration is about 0.75 ppb higher than the background value.

3.4 Sensitivity Study Results

3.4.1 Effect of building downwash

As described in Section 3.1, we used the PRIME model to determine the importance of building downwash for the two power plants selected for this study. A

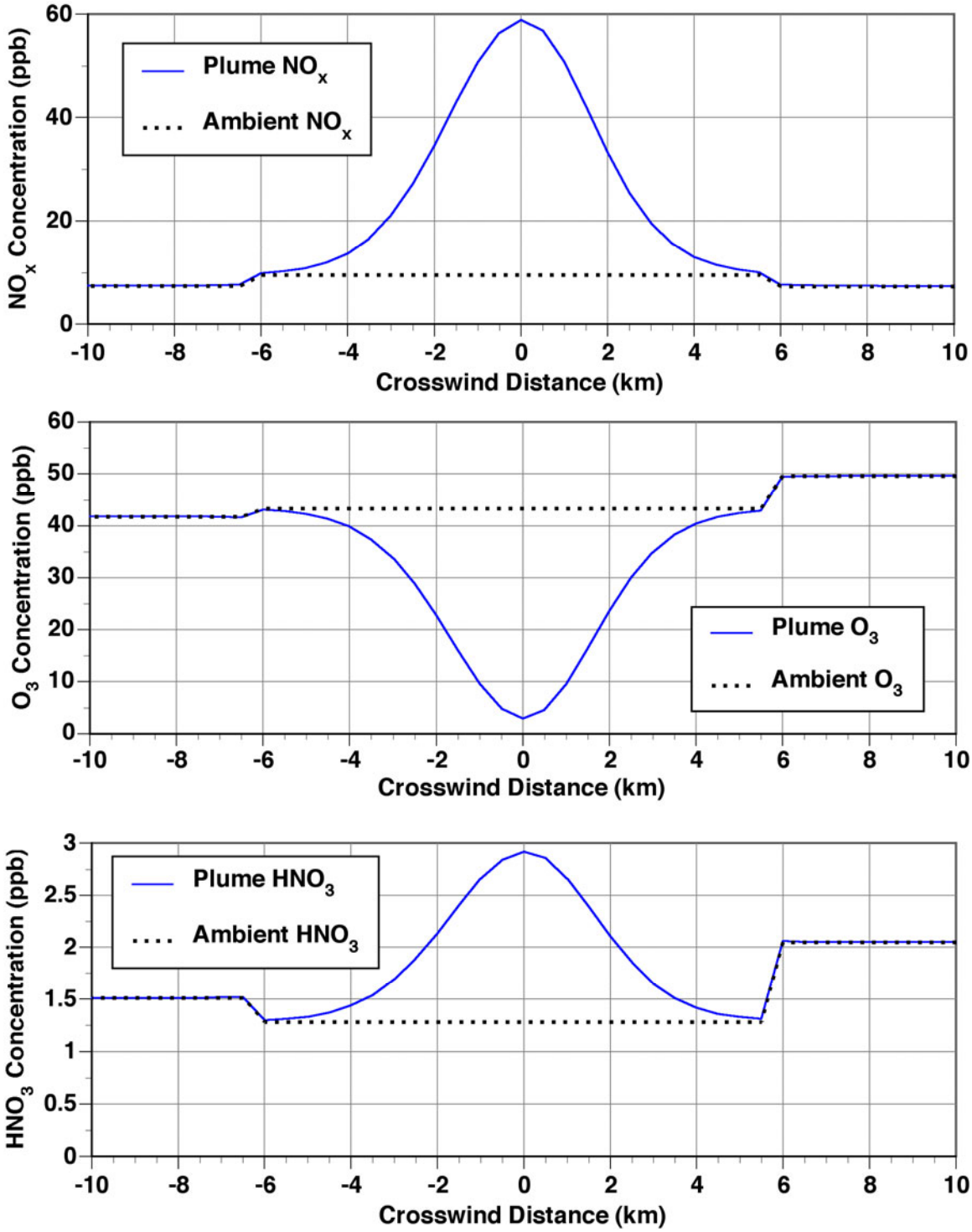

Figure 3-28. Across plume concentrations of NO_x, O_3, and HNO_3 25 km downwind of the Moss Landing power plant at 4 p.m. on August 6, 1990.

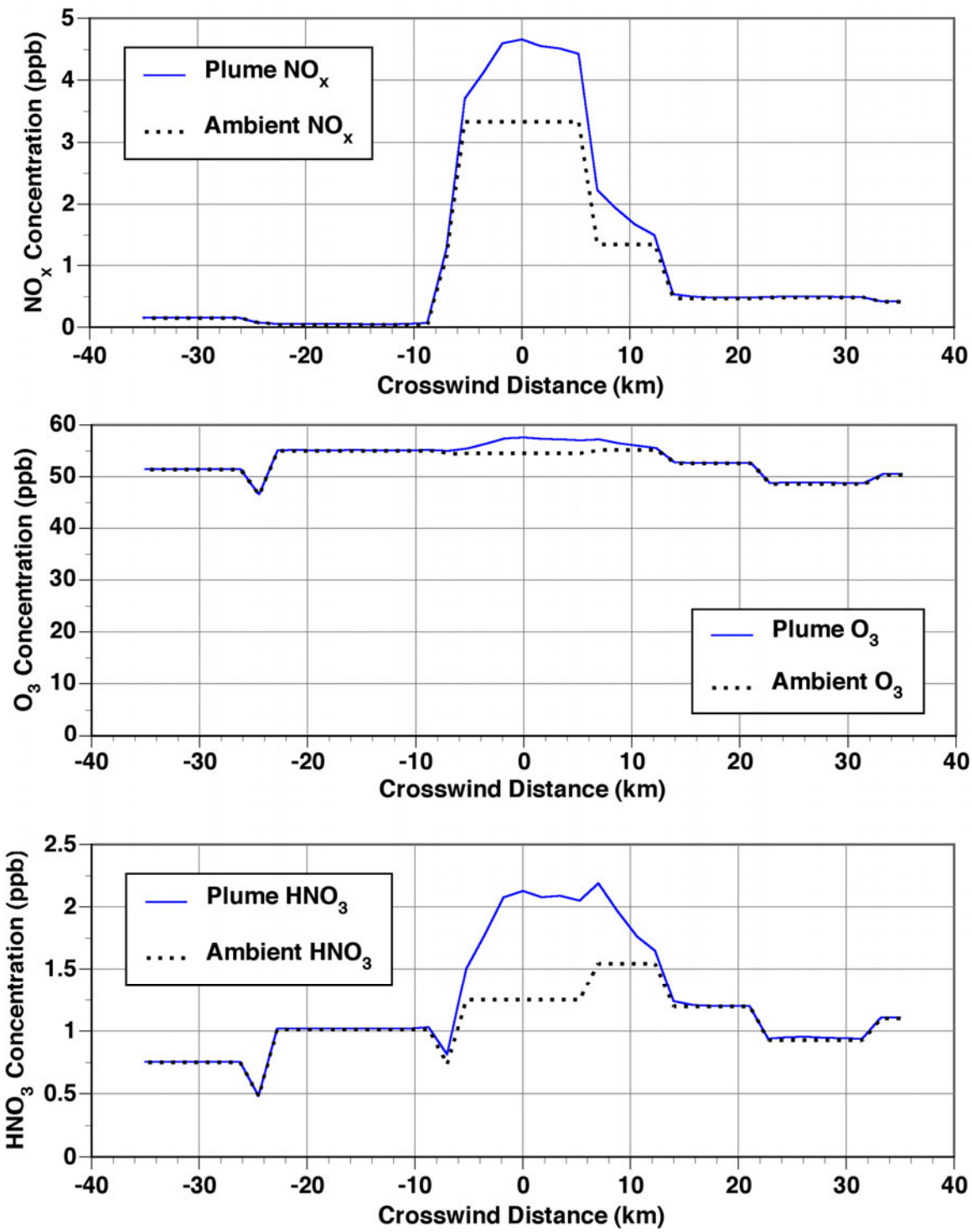

Figure 3-29. Across plume concentrations of NO_x, O_3, and HNO_3 75 km downwind of the Moss Landing power plant at 4 p.m. on August 6, 1990.

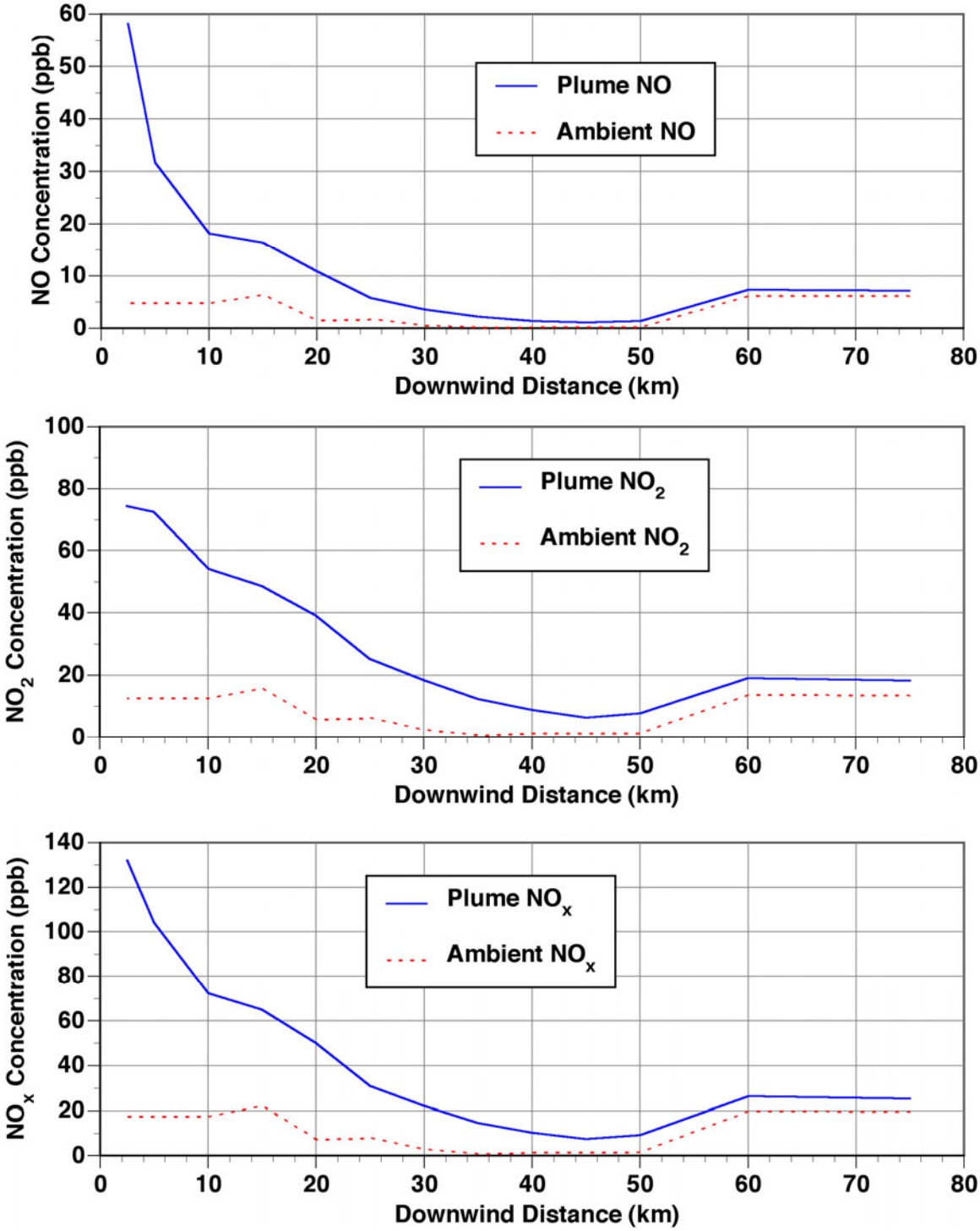

Figure 3-30. Plume centerline concentrations of NO, NO_2, and NO_x downwind of the Pittsburg power plant at 4 p.m. on August 6, 1990.

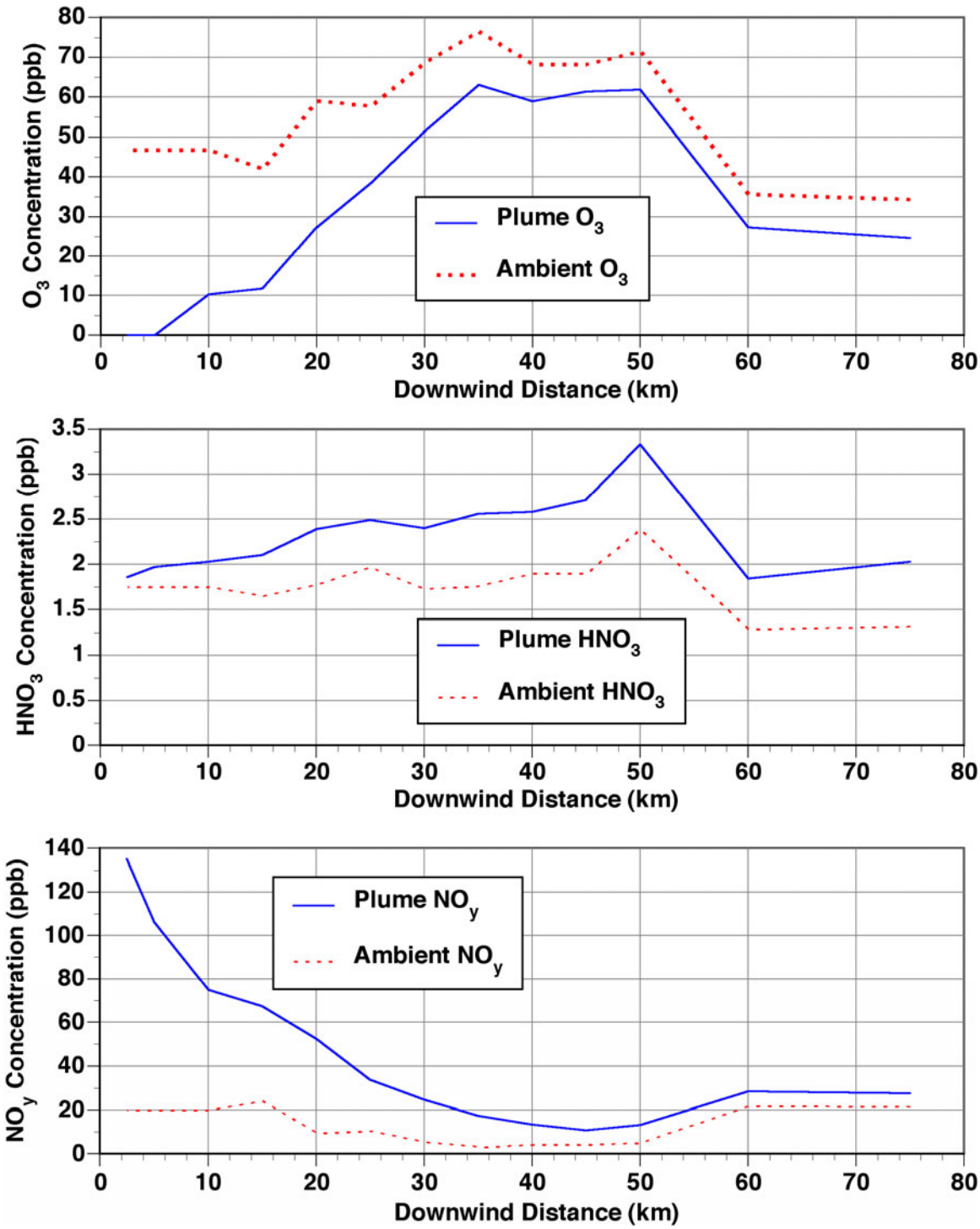

Figure 3-31. Plume centerline concentrations of O_3, HNO_3, and NO_y downwind of the Pittsburg power plant at 4 p.m. on August 6, 1990.

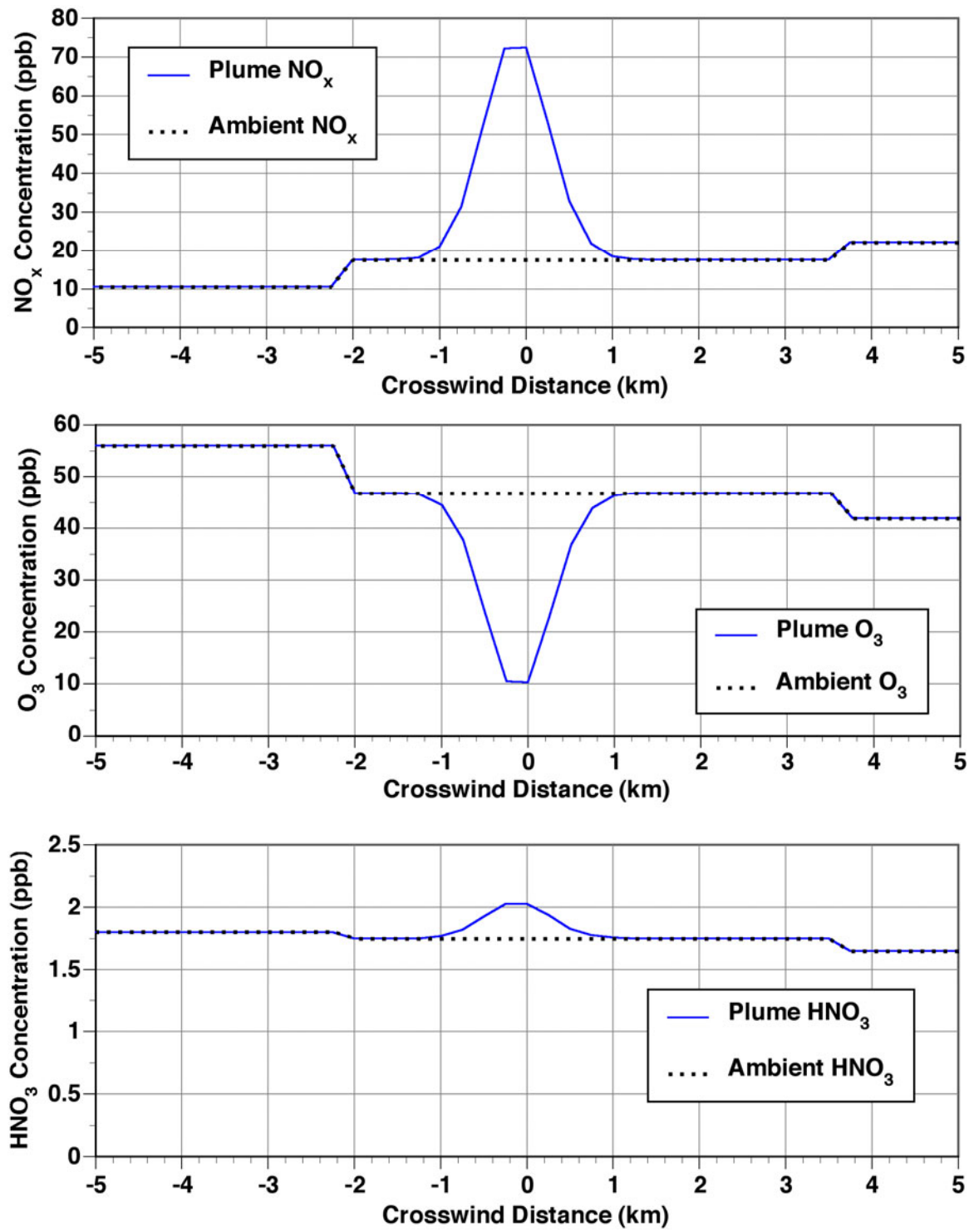

Figure 3-32. Across plume concentrations of NO_x, O_3, and HNO_3 10 km downwind of the Pittsburg power plant at 4 p.m. on August 6, 1990.

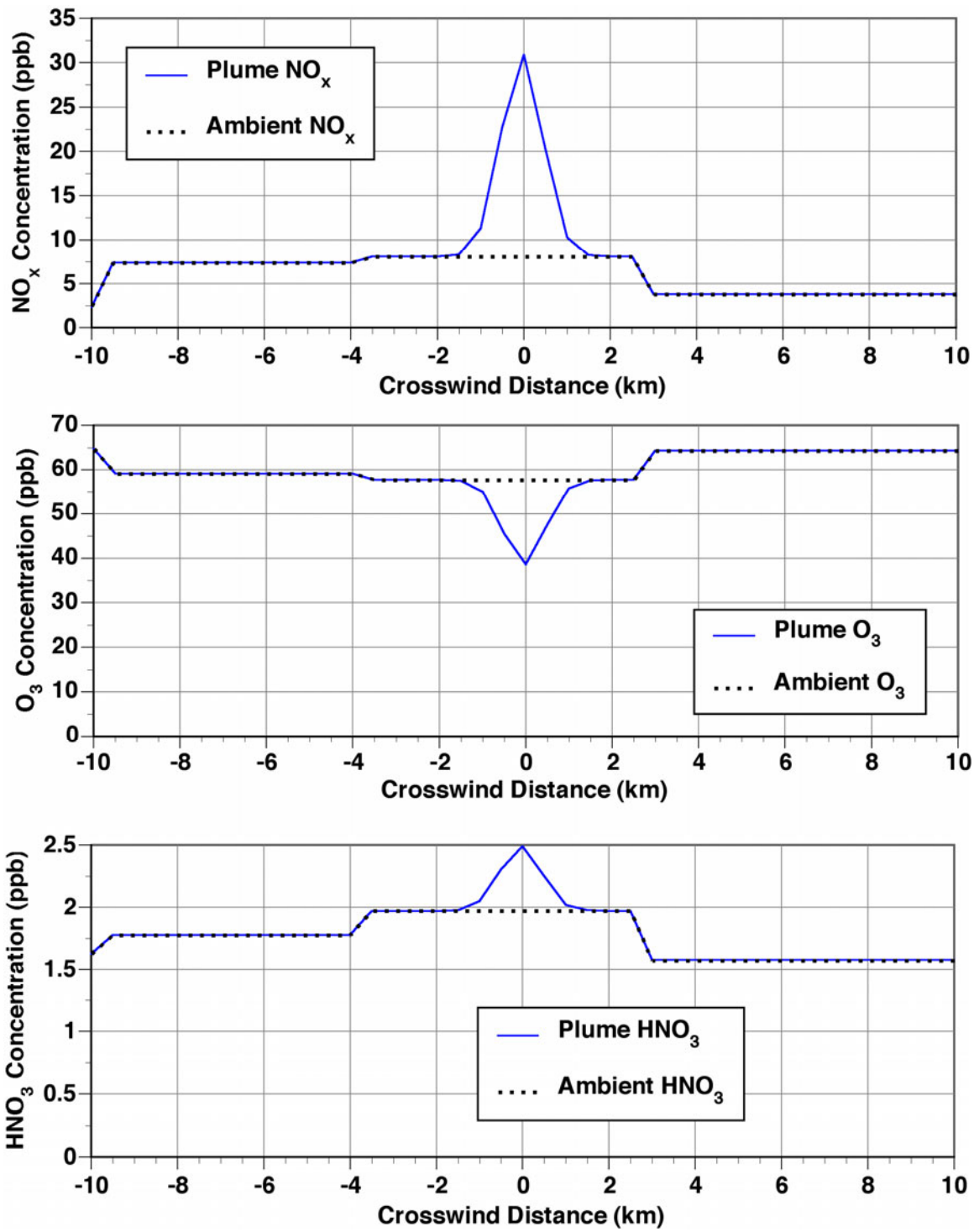

Figure 3-33. Across plume concentrations of NO_x, O_3, and HNO_3 25 km downwind of the Pittsburg power plant at 4 p.m. on August 6, 1990.

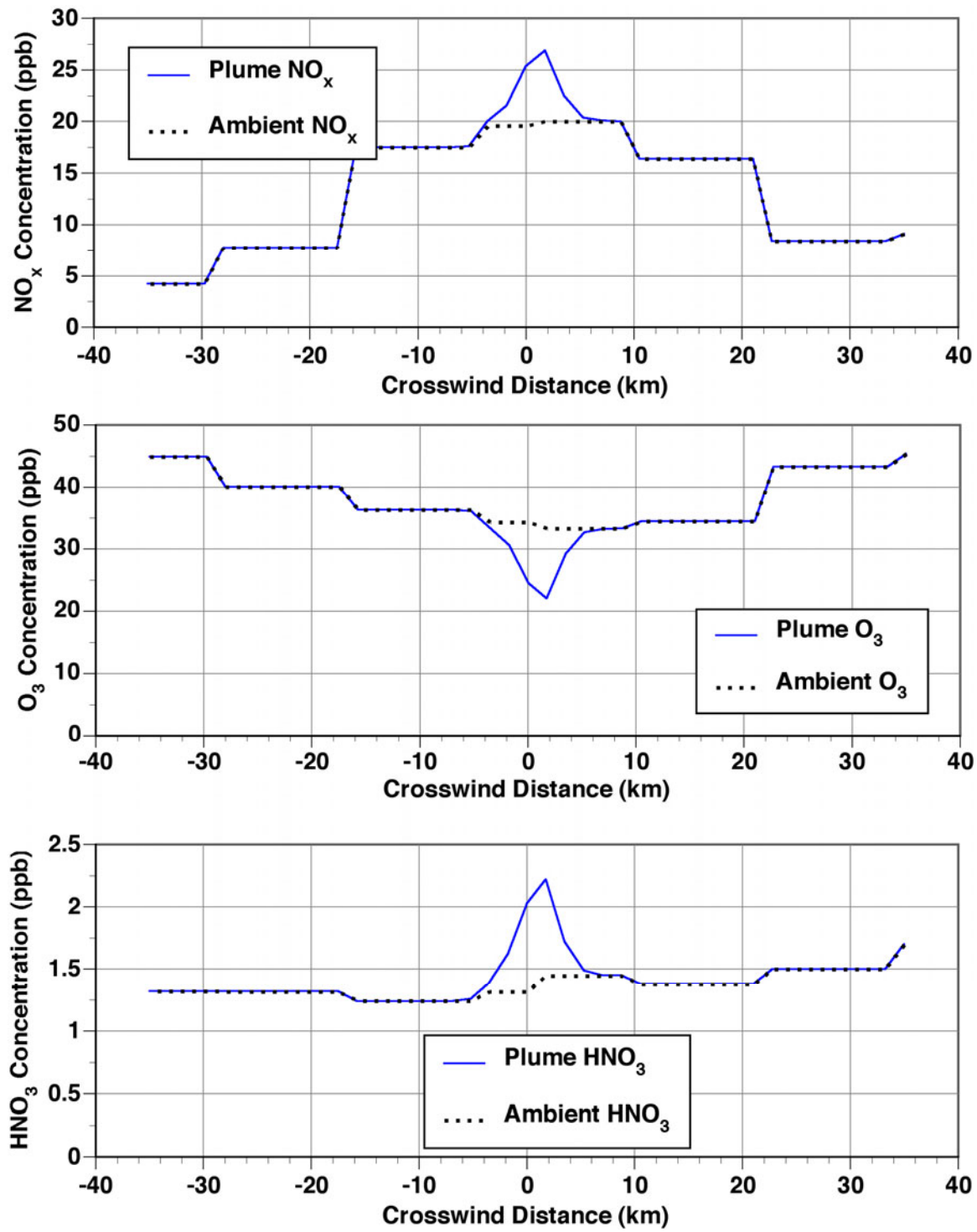

Figure 3-34. Across plume concentrations of NO_x, O_3, and HNO_3 75 km downwind of the Pittsburg power plant at 4 p.m. on August 6, 1990.

processor was written to extract the necessary meteorological information from the SAQM M1 and M2 files to drive the U.S. EPA ISC3/PRIME model. The building data provided by the CEC were processed using the modified BPIP processor provided with ISC3/PRIME to develop the necessary building configuration files for ISC3/PRIME.

The results with PRIME showed that adjacent buildings had no effect on the plume rise and dispersion characteristics of the Moss Landing power plant. Building downwash was predicted to be slightly important for the Pittsburg power plant and we conducted a sensitivity study in which the PRIME results were provided as modified stack parameters to SCICHEM for the Pittsburg source. Specifically, we provided the reduction in plume height predicted by PRIME as an adjustment to the stack height in SCICHEM. However, we did not account for the effect of downwash on plume dilution, since this was not possible within the SCICHEM framework.

The overall results in terms of the Pittsburg plume characteristics, such as plume widths, plume reactivity, etc. are qualitatively similar for the cases with and without downwash and are not presented here. In general, accounting for plume downwash lowers the average height of the Pittsburg plume slightly, from 30 m for the early morning simulation to negligible for the late afternoon simulation. The direction traveled by the plume also varies slightly by about 2 to 5 degrees when building downwash is considered.

As mentioned above, the downwash correction was only applied to the plume height, so that additional downwash effects, such as enhanced plume dispersion, could not be simulated and were ignored. For the conditions simulated here, we do not believe that these effects are likely to change our overall conclusions on the feasibility of tracking the Pittsburg plume. However, under conditions when plume downwash can be significant, it may be more difficult to track the plume.

3.4.2 Interaction of Pittsburg and Contra Costa plumes

In a second sensitivity study, we simulated all three power plants (Moss Landing, Pittsburg, and Contra Costa) with SCICHEM for the three meteorological scenarios.

Because Contra Costa is about 12 km downwind of Pittsburg under the flow conditions on August 6, there was some interaction between the Pittsburg and Contra Costa plumes.

Figure 3-35 presents the vertically integrated tracer concentrations at 8 a.m. when all three sources are simulated. Comparing the results with those shown in Figure 3-1, we see that the addition of Contra Costa results in a seemingly wider Pittsburg plume, indicating that the plumes from the two sources are possibly traveling in parallel directions with some overlap at their edges.

The vertically integrated tracer concentrations at 12 noon are shown in Figure 3-36. We see that, at 12 noon, the two plumes initially merge, then separate, with the Contra Costa plume going in a more southerly direction than the Pittsburg plume at a downwind distance of about 40 to 45 km from the Pittsburg power plant. Figure 3-36 shows a relatively high concentration spot downwind of Pittsburg and Contra Costa that appears to be disconnected from the continuous plume. This may happen under stagnant or recirculation conditions that could lead to separation of aged puffs and newer releases. Recall that Figure 3-36 is a snapshot of the vertically integrated tracer concentrations at a particular time.

The results for 4 p.m. are shown in Figure 3-37. As in the 8 a.m. results, it is not easy to distinguish the two plumes, except by comparison with Figure 3-4, which shows the Pittsburg plume only. The interaction of the Pittsburg and Contra Costa plumes again results in a wider plume.

Figure 3-38 shows the centerline plume concentrations downwind of Pittsburg for the base case study and the sensitivity study with the Contra Costa power plant at 12 noon on August 6, 1990. Note that the downwind locations are representative of the Pittsburg plume as determined in the base case study, and not the composite Pittsburg and Contra Costa plume. Figure 3-38 shows that, until about 25 km downwind of Pittsburg, the Contra Costa plume has a negligible impact on the Pittsburg plume at 12 noon. However, the interaction of the two plumes is evident between 25 and 60 km downwind of Pittsburg, with higher HNO_3 and NO_y concentrations and lower ozone concentrations in the combined plume study as compared to the base case study.

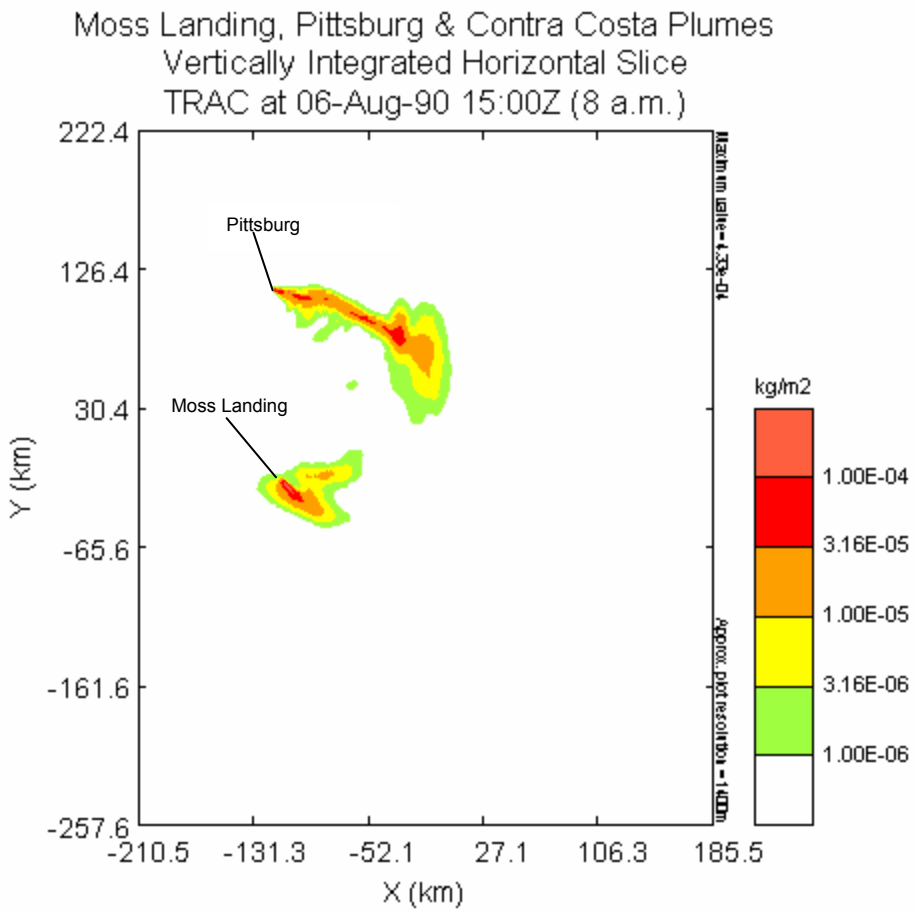

Figure 3-35. Vertically integrated tracer concentrations from the Moss Landing, Pittsburg and Contra Costa power plants at 8 a.m. on August 6, 1990.

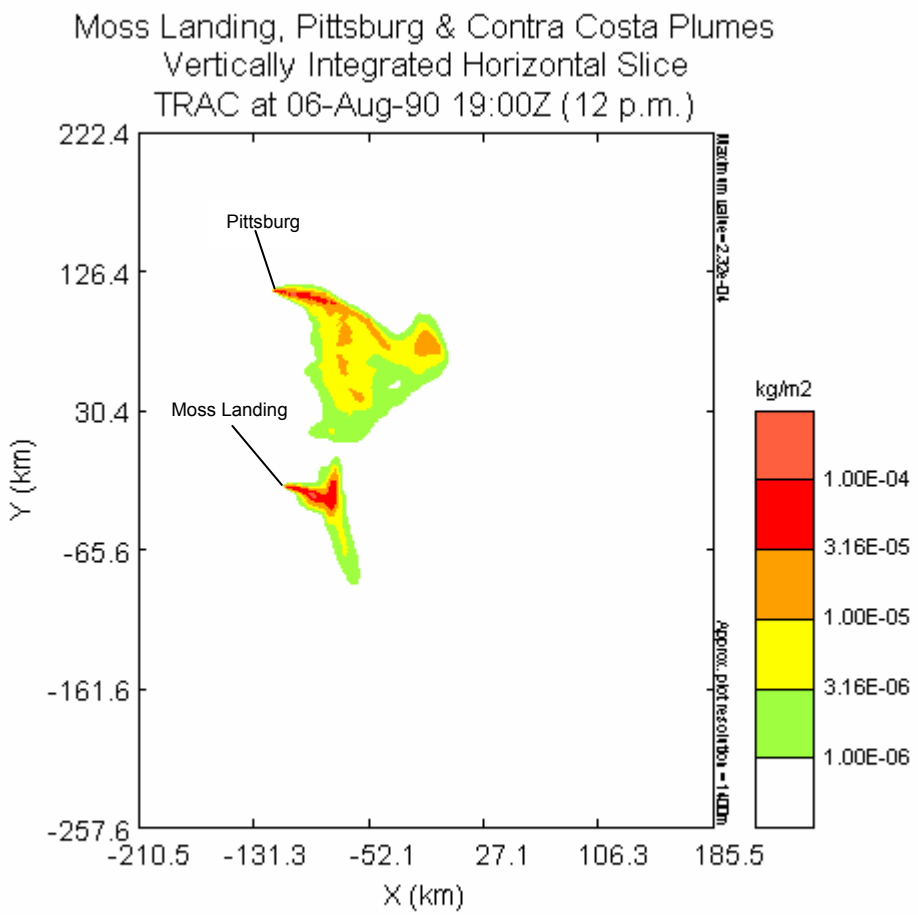

Figure 3-36. Vertically integrated tracer concentrations from the Moss Landing, Pittsburg and Contra Costa power plants at 12 noon on August 6, 1990.

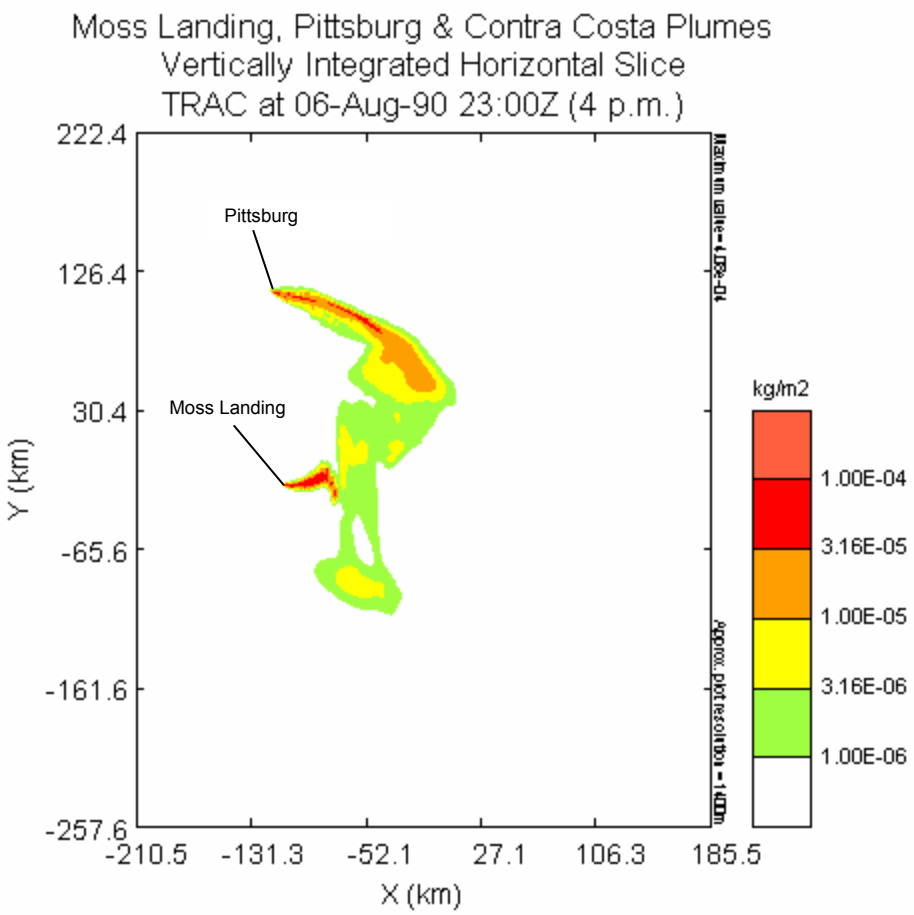

Figure 3-37. Vertically integrated tracer concentrations from the Moss Landing, Pittsburg and Contra Costa power plants at 4 p.m. on August 6, 1990.

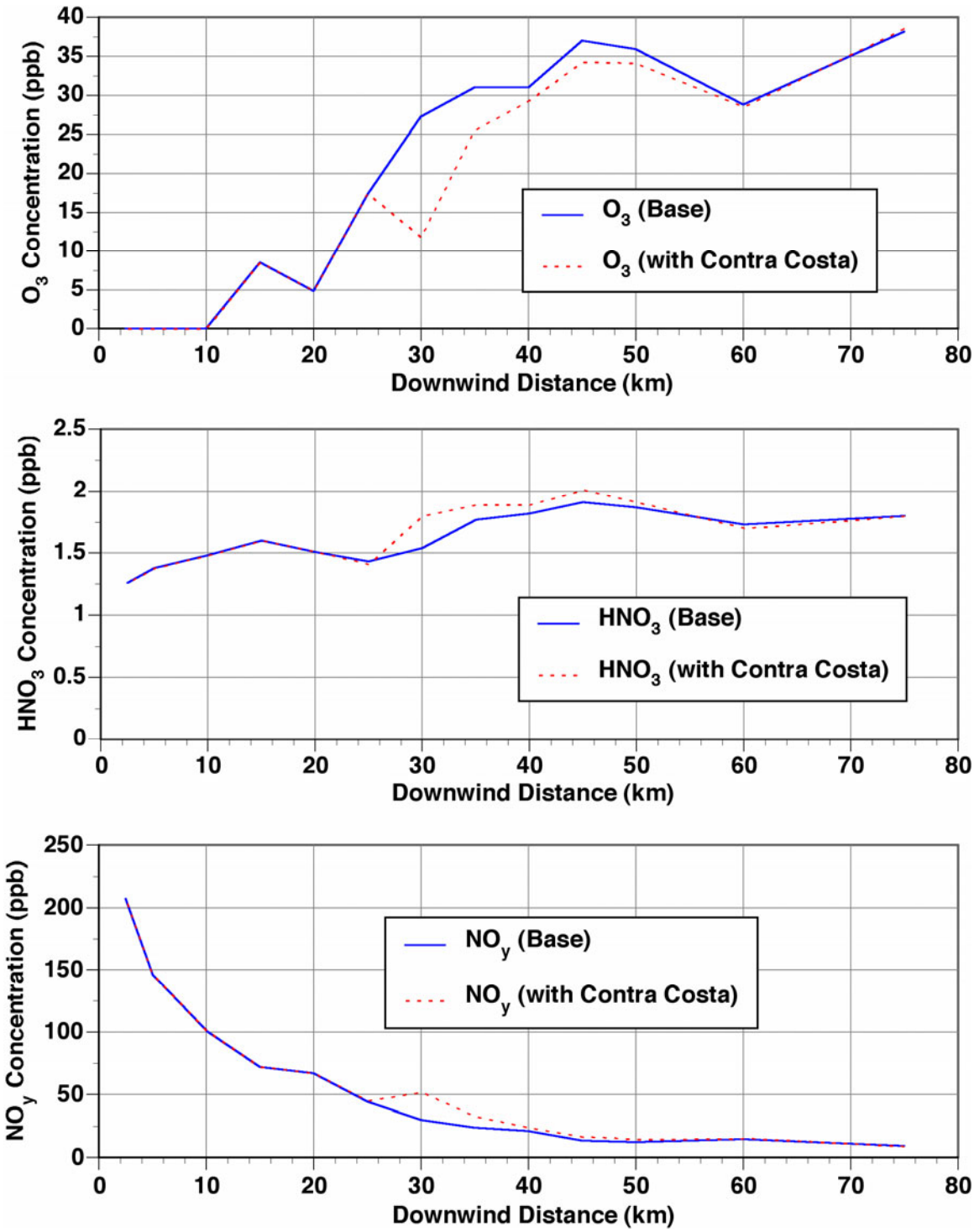

Figure 3-38. Plume centerline concentrations of O_3, HNO_3, and NO_y downwind of the Pittsburg power plant at 12 noon on August 6, 1990 for the base case and the sensitivity study with the Contra Costa power plant.

Figure 3-39 compares the 25 km crosswind concentrations at 4 p.m. in the Pittsburg plume from the two simulations. The concentrations in the Pittsburg plume centerline are unaffected by the Contra Costa plume, but the plume traverse shows the presence of the two plumes, resulting in an effective "wider" plume.

3.4.3 Effect of doubling ambient concentrations

This sensitivity study was conducted to determine how the reactivities of the Moss Landing and Pittsburg plumes would be affected by changes to the ambient conditions. Figure 3-40 shows the plume centerline concentrations of ozone, nitric acid, and NO_y at 8 a.m. downwind of Moss Landing. Comparing Figure 3-40 with Figure 3-6, which shows the same results for the base case study, we see initially larger ozone deficits in the plume followed by a rapid recovery to background levels. For example, at 5 km downwind, the ozone deficit is about 40 ppb (equal to the background level) in the base case study and about 80 ppb (again nearly equal to the background level) in the sensitivity study. At 35 km downwind in the base case study, the plume ozone concentration is 45 ppb, 10 ppb lower than the ambient value. In the sensitivity study, the plume ozone concentration is 100 ppb, 10 ppb lower than the ambient value. The nitric acid results show that the plume is more reactive when ambient concentrations are doubled. For example, at 10 km downwind, the excess nitric acid in the plume is slightly less than 1 ppb in the sensitivity study. In the base case study, the excess nitric acid is about 0.25 ppb.

The downwind concentrations for the Pittsburg plume at 8 a.m., shown in Figure 3-41, show the same response as the Moss Landing plume concentrations (compare Figure 3-41 with Figure 3-11, the corresponding results for the Pittsburg plume from the base case study).

Figure 3-42 shows the results at noon for the Moss Landing plume. Again, we see that the ozone deficits are larger in the sensitivity study than in the base case study (see Figure 3-16) since more background O_3 is available for titration by plume NO. At 30 km downwind, the ozone deficit is about 70 ppb (20 ppb in the plume versus an ambient concentration of 90 ppb) in the sensitivity study, while in the base case study, the

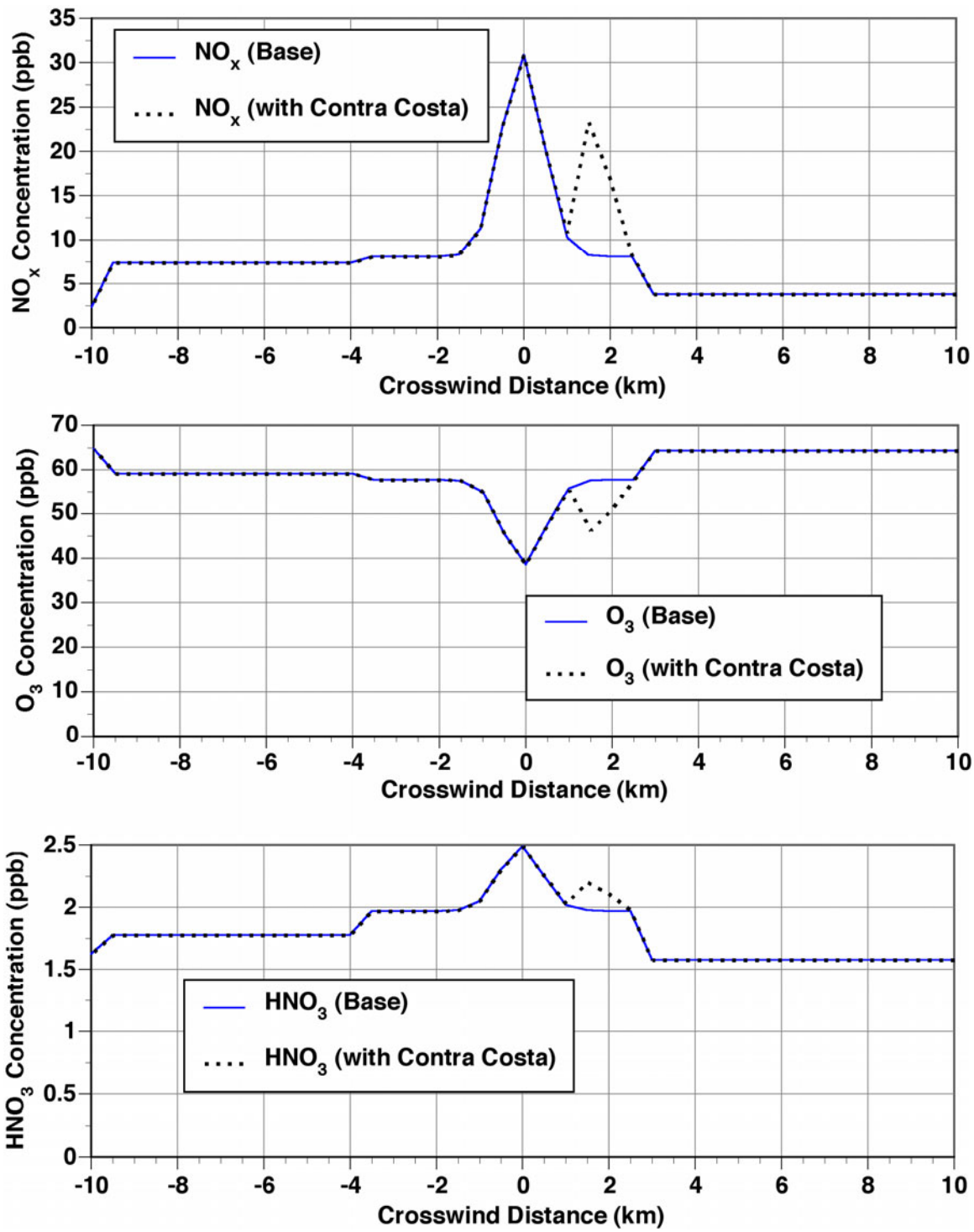

Figure 3-39. Across plume concentrations of NO_x, O_3, and HNO_3 25 km downwind of the Pittsburg power plant at 4 p.m. on August 6, 1990 for the base case and the sensitivity study with the Contra Costa power plant.

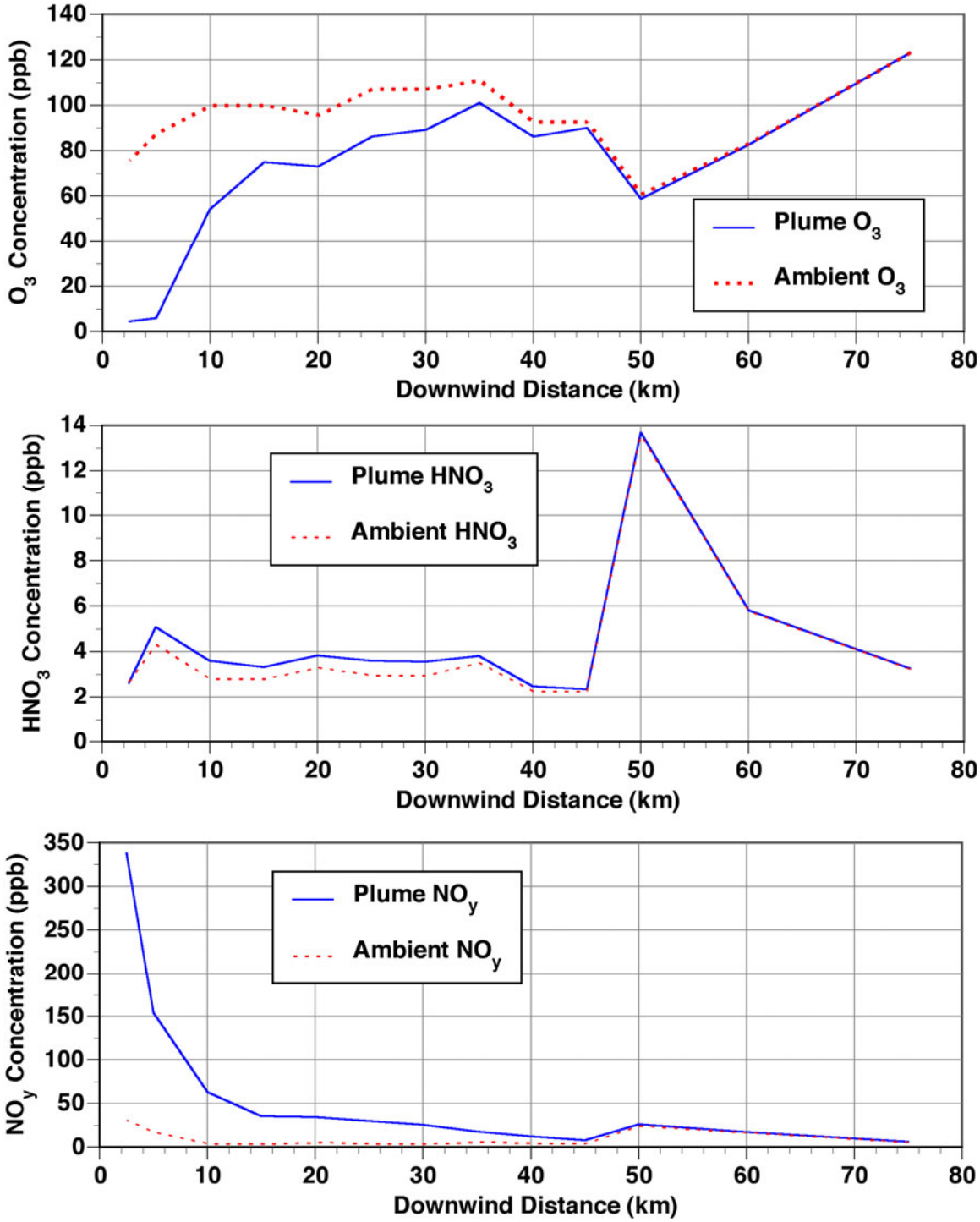

Figure 3-40. Plume centerline concentrations of O_3, HNO_3, and NO_y downwind of the Moss Landing power plant at 8 a.m. on August 6, 1990 with doubled ambient concentrations.

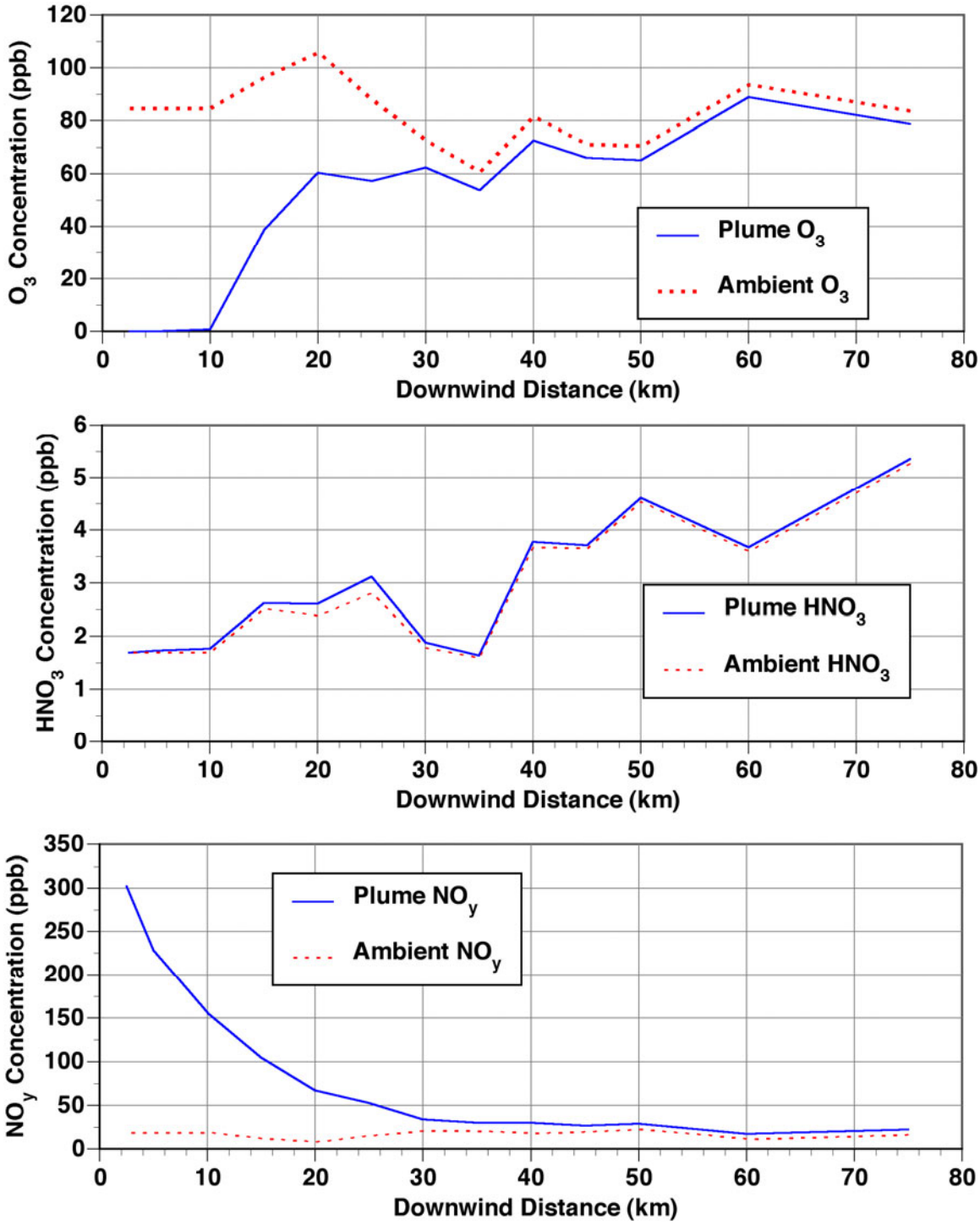

Figure 3-41. Plume centerline concentrations of O_3, HNO_3, and NO_y downwind of the Pittsburg power plant at 8 a.m. on August 6, 1990 with doubled ambient concentrations.

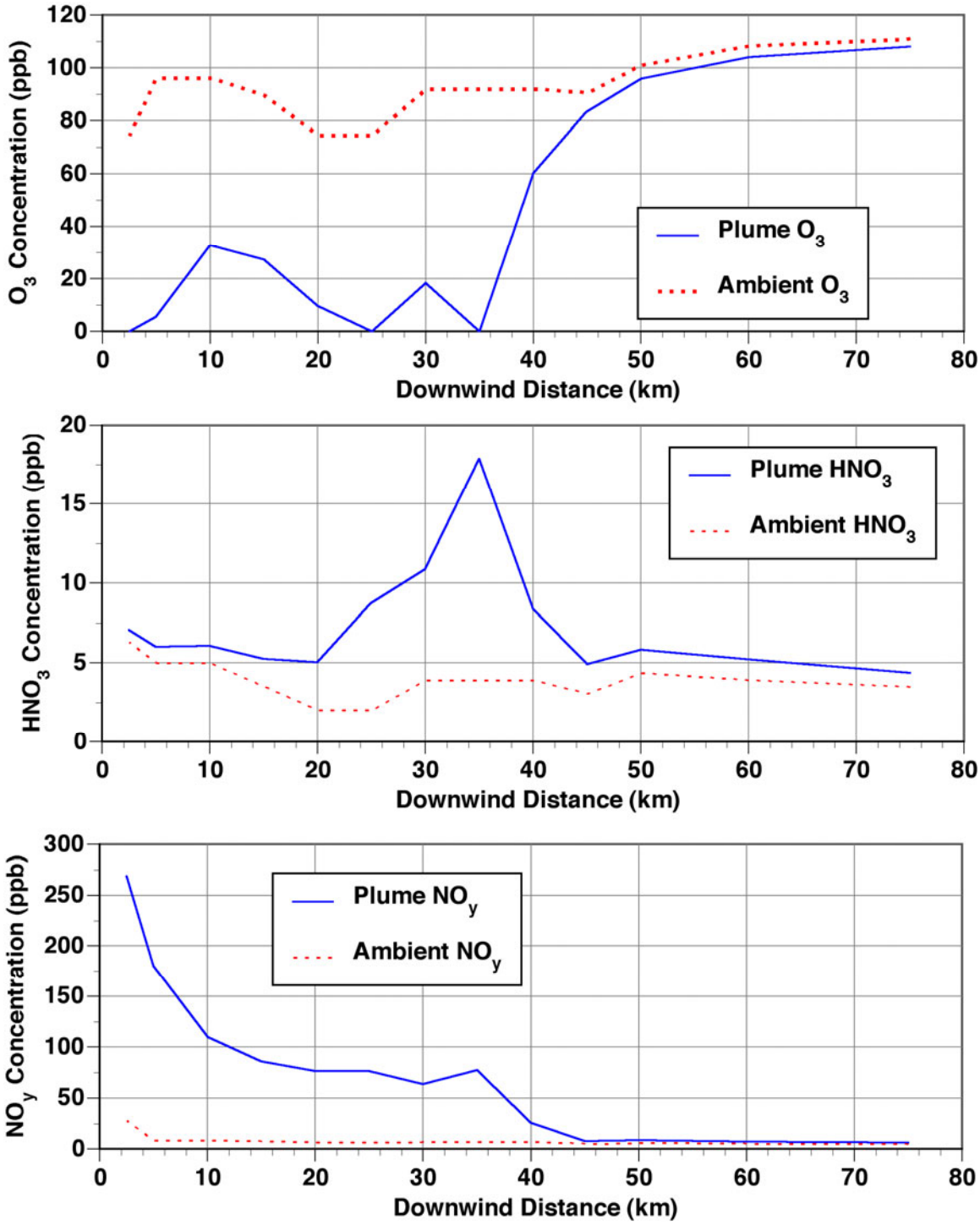

Figure 3-42. Plume centerline concentrations of O_3, HNO_3, and NO_y downwind of the Moss Landing power plant at 12 noon on August 6, 1990 with doubled ambient concentrations.

deficit is about 40 ppb (plume ozone concentration of about 5 ppb versus an ambient value of 45 ppb). More nitric acid is produced in the plume in the sensitivity study than in the base case study. The peak nitric acid excess in both studies occurs at about 35 km downwind, and is about 12 ppb for the sensitivity study versus 5.5 ppb for the base case study. The results are similar for the Pittsburg plume, shown in Figure 3-43.

Plume centerline concentrations downwind of Moss Landing at 4 p.m. are shown in Figure 3-44 for the sensitivity study. As in the previous results, the ozone deficits are larger in the sensitivity study than in the base case study, shown in Figure 3-26. At 20 km downwind, the ozone deficit is about 70 ppb in the sensitivity study as compared to a deficit of about 45 ppb in the base case study. Furthermore, the small ozone production in the plume at downwind distances greater than 50 km that was predicted in the base case study is not predicted in the sensitivity study. Again, more nitric acid is produced in the plume in the sensitivity study than in the base case study. The results are similar for the Pittsburg plume, as shown in Figure 3-45.

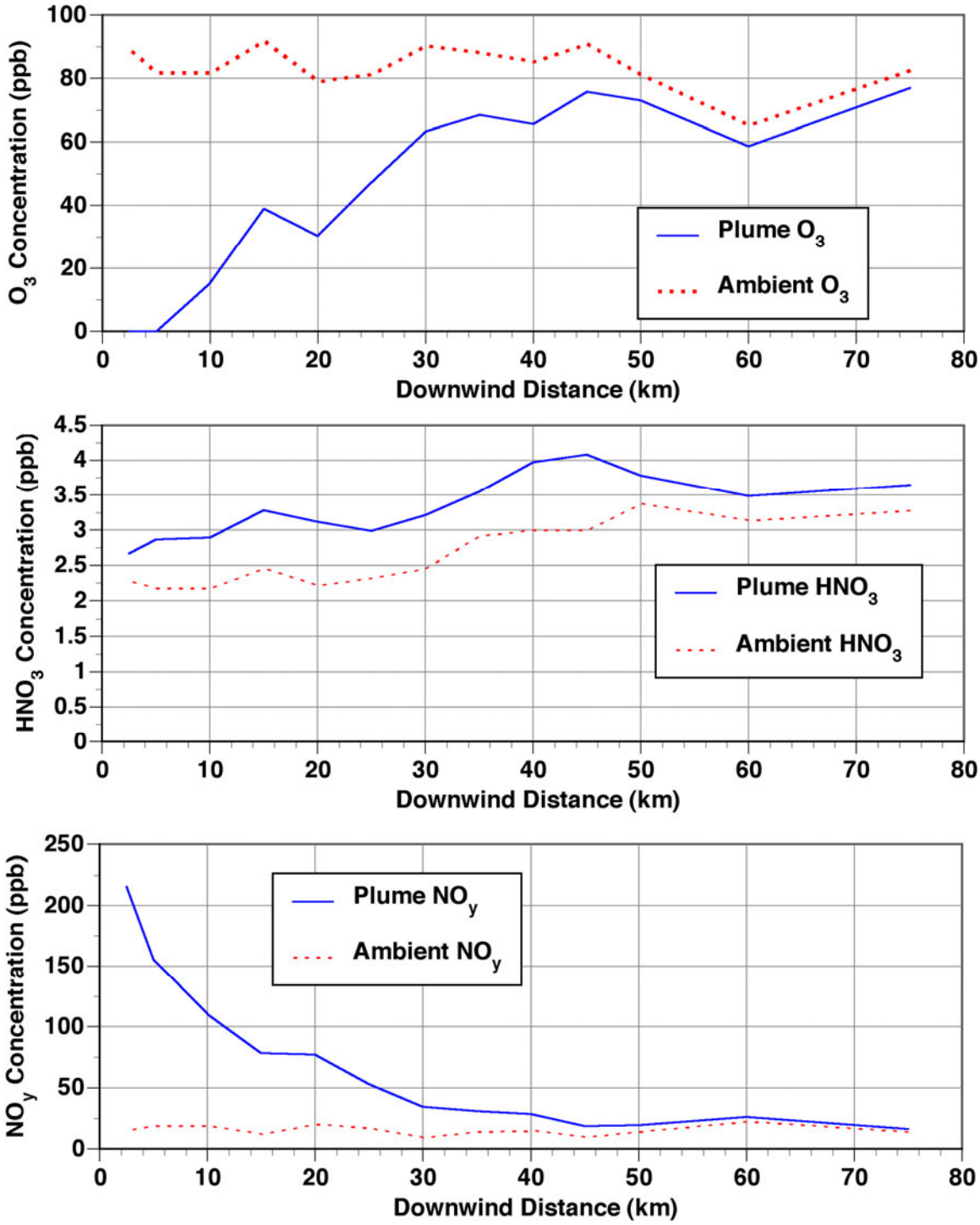

Figure 3-43. Plume centerline concentrations of O_3, HNO_3, and NO_y downwind of the Pittsburg power plant at 12 noon on August 6, 1990 with doubled ambient concentrations.

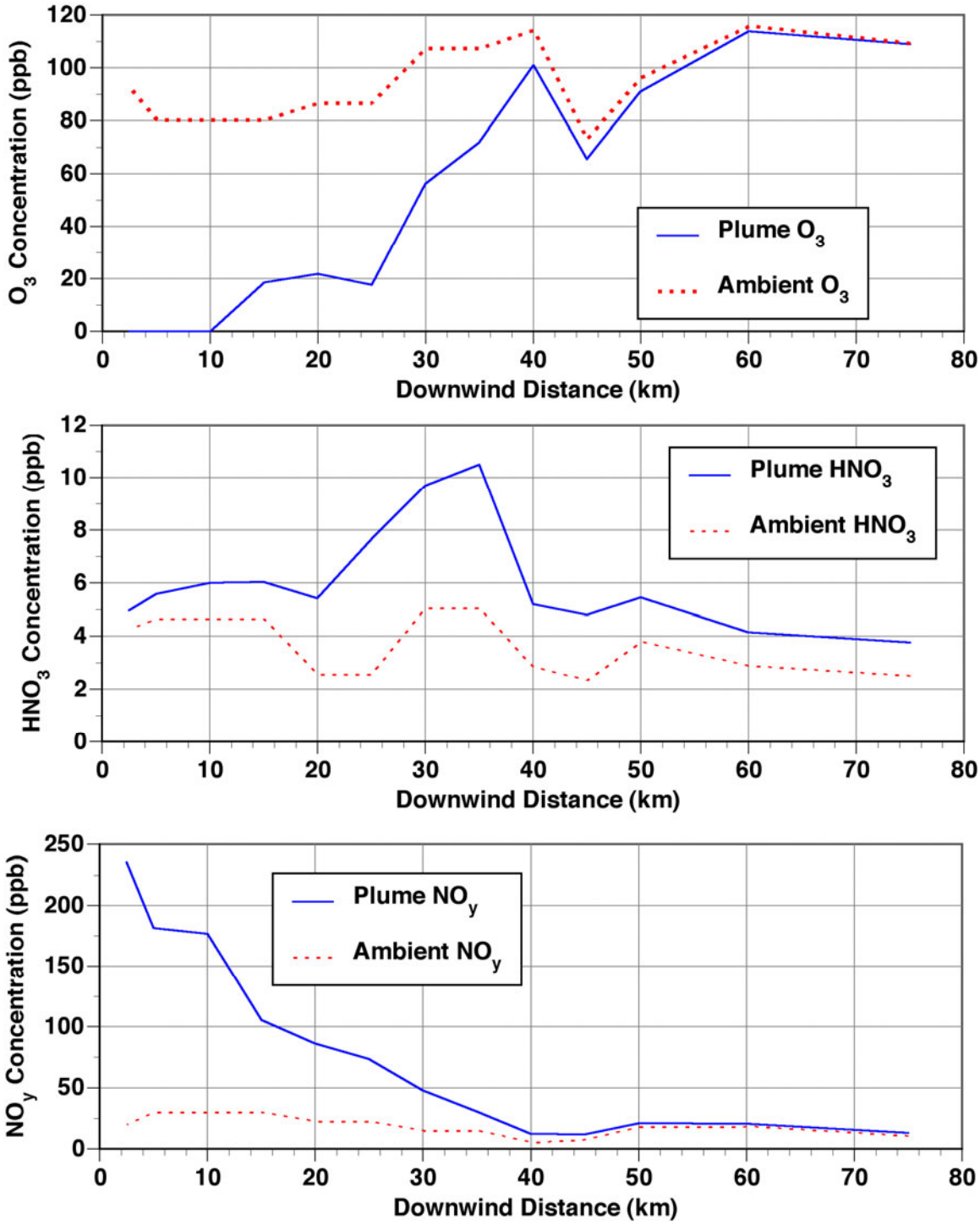

Figure 3-44. Plume centerline concentrations of O_3, HNO_3, and NO_y downwind of the Moss Landing power plant at 4 p.m. on August 6, 1990 with doubled ambient concentrations.

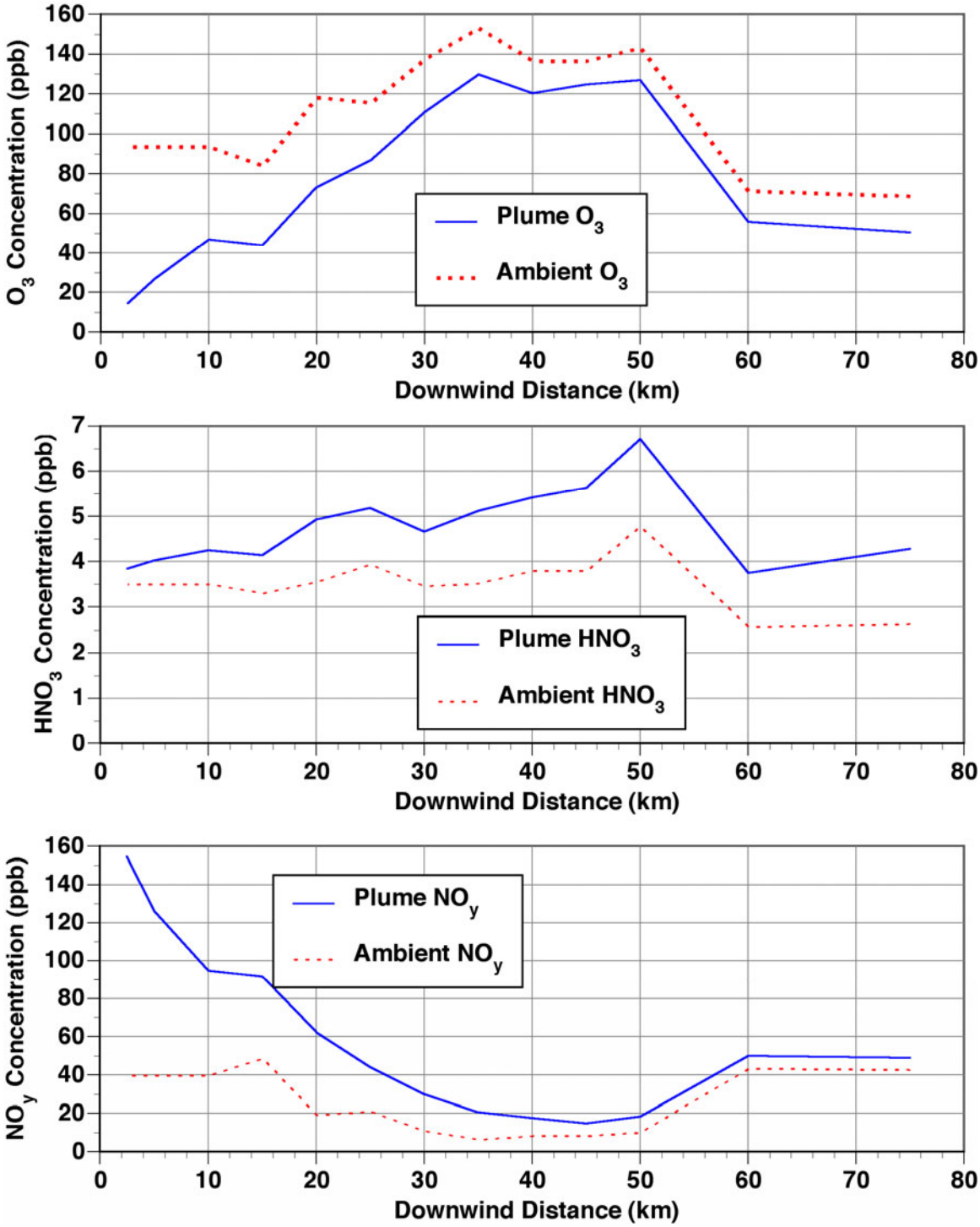

Figure 3-45. Plume centerline concentrations of O_3, HNO_3, and NO_y downwind of the Pittsburg power plant at 4 p.m. on August 6, 1990 with doubled ambient concentrations.

4. CONCLUSIONS AND RECOMMENDATIONS

The results from our modeling studies of the Moss Landing and Pittsburg plumes provide useful information on the physical and chemical characteristics of the two plumes and their expected behavior under conditions conducive to transport of the plumes in an easterly or southeasterly direction.

The results show some of the expected behavior of power plant plumes – depletion of ozone in the vicinity of the source, followed by gradual or rapid recovery of the ozone (depending on the time of day), as well as enhanced production of nitric acid as the plume travels downwind (again depending on the time of day. For the conditions simulated in this study, ozone formation in the plumes was not predicted, except in the afternoon simulation for the Moss Landing plume when a small amount of ozone above background levels was formed at downwind distances beyond 50 km.

For the conditions simulated here, the Pittsburg plume does not disperse as rapidly as the Moss Landing plume. The Pittsburg plume is always narrower than the Moss Landing plume, typically by a factor of two. In addition, the Moss Landing plume centerline tends to be closer to the ground than the Pittsburg plume. A possible explanation for these differences is that the Pittsburg plume travels over flat terrain, while the Moss Landing plume encounters complex or hilly terrain within 20 to 25 km of the source.

Because the Moss Landing plume is diluted faster than the Pittsburg plume, the Pittsburg plume can generally be distinguished from the background for larger downwind distances than the Moss Landing plume. Furthermore, the Pittsburg plume is less reactive than the Moss Landing plume in terms of both the production of nitric acid and recovery of ozone.

These differences in the chemical characteristics of the two plumes are likely due to differences in the environments in which the NO_x emissions from the two sources are released. The results suggest that the Pittsburg plume is initially in a VOC-limited environment, while the Moss Landing plume is in a NO_x-limited environment. These results are consistent with those of Lu and Chang (1998) who used SAQM results to assess ozone sensitivities to emissions reductions in the SARMAP modeling domain.

They are also consistent with the theoretical results of Karamchandani and Seigneur (1999) who conducted simulations of a power plant plume for a range of background concentrations and meteorological conditions. They found enhanced production of nitric and sulfuric acids when background VOC levels were increased.

For the early morning simulation ending at 8 a.m., the Moss Landing plume is indistinguishable from the background beyond a downwind distance of 50 km. The ozone in the plume is initially depleted but recovers to background levels by 50 km. downwind. A very small amount of nitric acid (generally less than 0.2 ppb) is formed in the plume during the early morning simulation. The Pittsburg plume can be discerned at downwind distances greater than 50 km. The ozone deficit is not completely recovered even at a downwind distance of 75 km. There is negligible production of nitric acid production in the Pittsburg plume in the early morning simulation.

For the mid-day simulation ending at 12 noon, there is significant nitric acid production in the Moss Landing plume. The peak nitric acid concentration in the plume centerline occurs at 35 km downwind, when the plume HNO_3 concentration is almost 7.5 ppb, compared to the ambient value of 2 ppb. The ozone in the plume is depleted to a downwind distance of 35 km but recovers rapidly to the background value by 50 km downwind. For the Pittsburg plume, the ozone recovery is incomplete even at a downwind distance of 75 km, when the ozone deficit is about 2 ppb. More nitric acid is formed in the Pittsburg plume in the mid-day simulation than in the early morning simulation, but the nitric acid production is still much smaller than that in the Moss Landing plume. The peak nitric acid excess in the Pittsburg plume is more than a factor of ten smaller than the Moss Landing peak.

For the afternoon simulation ending at 4 p.m., the ozone in the plume recovers rapidly from zero at 20 km downwind to the background level by 45 km. At downwind distances greater than 50 km, a small amount of ozone in excess of the background is produced in the plume. There is significant nitric acid produced in the plume at all downwind distances, even at 75 km from the source, but the peak nitric acid concentration at about 35 km downwind is smaller than the 12 p.m. peak. There is again incomplete recovery of ozone in the Pittsburg plume, but more nitric acid is produced in

the plume than in the mid-day simulation. However, the nitric acid production in the Pittsburg plume is still smaller than in the Moss Landing plume.

There is no effect of building downwash on the Moss Landing plume, and the effect on the Pittsburg plume is minor, resulting mainly in small changes in the direction of the plume and in the plume centerline height. However, the plume downwash simulations that were conducted in this work only involved corrections to the plume height and did not take into account the effect of downwash on plume dilution. This effect may make it harder to track the plume under conditions when downwash is important.

There is frequent interaction between the Pittsburg and Contra Costa plumes when the winds are from the west or the north-west. The two plumes sometimes overlap completely, resulting in higher plume centerline concentrations or travel in parallel directions, resulting in two peaks in the crosswind plume profiles.

When ambient concentrations of all species (including radicals) are doubled, both the Moss Landing and Pittsburg plumes are more reactive with respect to nitric acid formation – the amount of nitric acid produced in the two plumes is a factor of two to three times the base case value. The ozone recovery in the two plumes is more rapid than in the base case, particularly for the early morning simulation. However, there is no ozone production in excess of the background in the two plumes, even for the 4 p.m. Moss Landing simulation.

These results indicate that the Pittsburg plume can be sampled at larger downwind distances than the Moss Landing plume. However, because the plume is narrower, it is important to identify the flow direction accurately. Furthermore, mid-day and afternoon measurements should focus on measuring NO_x and nitric acid (or NO_y) concentrations in the plume at both near and far downwind distances and ozone concentrations near the source, since there is negligible formation of ozone in the plumes above background levels, at least for the conditions simulated in this study.

The results from our simulations suggest that, under certain conditions, the Moss Landing plume can be tracked as far as 50 km downwind from the source, while the Pittsburg plume can be tracked out to downwind distances of 75 km. However, the actual downwind distances at which the plumes can be discerned may be smaller under highly

dispersive conditions, or because of instrument limitations or background conditions that are significantly different from those used here. In the 1995 SOS Nashville/Middle Tennessee Ozone Study referred to in Section 2, the Cumberland plume was tracked to downwind distances greater than 100 km. However, the NO_x emissions from the Cumberland power plant (approximately 124,000 metric tons per year in 1995) were more than an order of magnitude higher than those from any of the power plants simulated here.

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