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Project Summary

Project CONDORS—Convective Diffusion Observed by Remote Sensors

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This data report presents results from two diffusion experiments conducted at the Boulder Atmospheric Observatory (BAO) of the National Oceanic and Atmospheric Administration (NOAA) in 1982 and 1983. The objective was to compare diffusion in the atmospheric convective boundary layer with that observed in laboratory tank experiments and numerical computer models. In both experiments at the BAO, two different tracers, oil fog and aluminized chaff, were released simultaneously and tracked by lidar and radar, respectively, for periods up to two hours. In 1982, both tracers were released from the same surface or elevated point; in 1983, the two were also released from separate levels, the oil fog from near the surface, the chaff from an elevated point on the tower. The 1983 experiment included tracer gas releases with *in situ* samplers measuring surface concentrations downwind of the tower. The BAO tower provided data on the mean and turbulent state of the atmosphere, while mixing depths were monitored by balloon soundings, sodar, lidar, and radar. A detailed description of the experiment and the measurements obtained from the different sensors is provided. The strengths and limitations of the experiment are discussed in the context of case studies.

This Project Summary was developed by EPA's Atmospheric Sciences Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Project CONDORS (Convective Diffusion Observed by Remote Sensors) was undertaken to provide field data on diffusion in three dimensions at short ranges, 0.1 to 3.5 km, in convective conditions. These conditions prevail over land during sunny to partly cloudy days with light to moderate wind speeds, especially when surface heating is moderate to strong. This volume is a data report on Project CONDORS, later to be followed by scientific analyses of the data published in peer-reviewed journals.

The need for such an experiment became evident after unexpected results for vertical diffusion were obtained from laboratory experiments in a convective water tank by Willis and Deardorff (1976a, 1976b, 1978, 1981) and from computer modeling experiments by Lamb (1978, 1979). The concentration (X) patterns in downwind distance (x) and in height (z) were substantially different from those resulting from conventional Gaussian diffusion models. For releases near $z = 0.5\ z_i$, where z_i is the mixing depth, maximum surface X was found to be about twice that predicted by Gaussian models. (Mixing depth refers to a layer of vigorous mixing due to convective turbulence produced by surface heating; this layer is always capped by a layer of stable air, which often is marked by a temperature inversion just above z_i.) For elevated releases, the centerline of maximum averaged X was observed to descend with distance from the source height, nearly to the surface; thereafter, the plume behaved much like a surface release. For surface releases, the maximum averaged X remained near the surface up to a time typifying the flow of air from downdrafts to updrafts (thermals); then it rapidly lifted into the upper half of the mixing layer.

The above-mentioned laboratory and computer modeling experiments, as well as turbulence measurements in the mixing layer at a variety of sites, also showed the importance of the length scale z_i and the velocity scale w^* to turbulence and diffusion in convective boundary layers (CBLs) ($w^* = (H^* z_i)^{1/3}$, where H^* is the vertical flux of buoyant accelerations produced by sensible heating and water vapor flux near the surface; for surfaces not very moist, $H^* \simeq (g/T)\overline{w'T'}$, where g is gravitational acceleration, T is absolute temperature, and $\overline{w'T'}$ is the vertical turbulent flux of temperature variations). Average diffusion patterns in CBLs scale best with z_i and the time scale z_i/w^*. The time after release, t, can be estimated as $x/\bar{u}$ (the mean wind speed, $\bar{u}$, is almost constant with z through most CBLs, because of vigorous vertical mixing). Diffusion results from various experiments in CBLs tend to agree well when expressed in terms of dimensionless time or distance, $X = (x/\bar{u})w^*/z_i = tw^*/z_i$. Unfortunately, very few past diffusion experiments in the field included sufficient meteorological measurements to determine w^* or z_i; furthermore, they are limited to measurements of X at the surface or on towers no higher than 62 m. Measurements of X are needed up to $z \simeq z_i$, which is usually of the order of 1000 m.

To verify the new laboratory results for convective diffusion, particularly the non-Gaussian vertical behaviors, data from a field study were needed. The CONDORS field experiment was designed to go beyond the limitations of past diffusion experiments in two ways. First, a large number of high-quality meteorological measurements were made so that essential quantities like w^*, z_i, and $\bar{u}$ could be determined with accuracy and redundancy. Many less essential measurements were also collected; e.g., unusually detailed information on wind direction statistics. Second, remote sensors were used to define mean X fields in three dimensions through depths up to 2000 m, easily encompassing z_i. Two independent tracer-sensor systems were used, lidar to detect oil fog and Doppler radar for detection of metalicized "chaff." Also, limited conventional gaseous tracer measurements were made at the surface; these served primarily to test the inferences made about conservative-source X on the basis of observed distributions of oil fog and chaff, which are not conservative (oil fog droplets tend to vaporize and chaff tends to settle out).

Operational Plan

The CONDORS experiment was carried out in 1982 and 1983 at NOAA's Boulder Atmospheric Observatory (BAO), operated by the Wave Propagation Laboratory (WPL), under an interagency agreement between EPA and WPL. In 1983, an additional interagency agreement between EPA and NOAA's Air Resources Laboratory Field Office (ARLFO) provided for sampling and analysis of gaseous tracer releases. WPL provided the site, most of the personnel, meteorological measurements, radar and lidar measurements, and followup data processing.

The 1982 experiments consisted of four runs of two hour's duration carried out on separate days in September. The four runs were intended primarily as trial runs to test the adequacy and the limitations of the two remote sensor techniques. The oil fog generator and chaff dispenser were located within a few meters of each other to permit direct comparisons of the observed X distributions. The runs were split evenly between elevated releases and surface releases. These experiments were successful enough to provide six averaging periods with usable chaff and/or oil fog distributions plus adequate meteorological data.

The 1983 experiments included surface sampling of tracer gases and consisted of eight runs of two hour's duration on separate days in late August to mid-September. Based on conclusions following some analyses of the 1982 runs, it was decided to use the chaff only in the elevated release mode in 1983. Two more runs with collocated elevated releases were made; during the remaining six runs, the oil fog was released from the surface so that independent measurements of simultaneous elevated and surface releases could be made. These eight runs provided 11 averaging periods with relatively steady meteorological variables and good chaff and/or oil fog measurements.

Preparation for a typical run began with a check of daily National Weather Service forecast maps. A forecast including clear to partly cloudy skies, Colorado under the influence of a surface high, and light to moderate geostropic winds was considered favorable for a run; all field personnel were notified of the weather outlook. Near sunrise on promising days, a rawinsonde was released at the BAO and tracked by double theodolite to about 3000 m AGL. The data were quickly processed into temperature, humidity, wind speed and direction profiles and transmitted to the main WPL laboratory in Boulder. This sounding, supplemented by the 1200Z sounding at Stapleton Airport in Denver, was the main basis for deciding whether to send personnel to their stations in the field, about 25 km east of Boulder. In 1983, the sounding data were input into a numerical model for z_i development; this facilitated the decision making, especially the choice of optimum times to initiate runs (slow z_i growth during runs was desired).

At the CONDORS site, z_i development was monitored using tower profiles and turbulence measurements up to 300 m, acoustic sounder records up to about 600 m, lidar reports of haze heights, and radar reports of heights of natural reflectors (thought to be insects). When z_i developed into the desired range and the winds on the tower entered into the desired speed range (2 to 6 m/s) and direction sector (NE to SE), a run initiation time (RIT) was called. The elevated source height was chosen on the basis of predicted z_i for the middle of the run, attempting to set this height at about 1/4 or 1/2 z_i to duplicate the laboratory and computer modeling runs. About 15 minutes were required for the release height to be reached by the carriage on the 300-m tower. Tracer releases were begun 10 to 20 minutes prior to RIT to allow plume transport out to the distances of greatest interest (about $z_i\bar{u}/w^*$). The lidar crew was advised of preferred lidar azimuths, which also depended on the expected value of the length scale $z_i\bar{u}/w^*$. Sampler, lidar, and radar acquisition began at RIT and continued for two hours, or slightly longer if wind velocity remained in the acceptable range (during both years at least one run was aborted due to sudden wind direction change).

Siting

The BAO site was chosen primarily for the excellent meteorological measurements available on the 300-m tower and the convenience of a release platform that can quickly be elevated up to 300 m (the carriage attached to the west side of the tower). Another convenient factor was the close proximity of WPL's personnel and facilities, including the Doppler radar, the lidar, acoustic sounders, data loggers, and computers. The site has both advantages and disadvantages for this type of experiment. The terrain is gently rolling, neither "ideal" nor complex, and is somewhat typical of developed land surface. Convective conditions predominate during spring, summer, and fall days; late summer was chosen for the experiment because z_i is likely to be in the desired range, and cloudy or rainy spells are less likely than in the fall. During convective conditions, the midday wind direction is almost always from the NE, E, or SE. This is thought to be caused by upslope flow on the heated eastern slopes of the Front Range of the Rocky Mountains, 25 to 50 km west of the BAO. The prevalence of winds from one direction sector made it easier to effectively site the lidar, the radar, and samplers during CONDORS. On the other hand, the easterly flow in the mixing layer was almost always opposed to the upper winds; as z_i grows and entrains upper air, momentum from above mixes downward; the opposition of upper and mixing layer wind directions at this site probably causes more variability in wind speed and direction than is common in CBLs farther from large mountain ranges.

Siting of the sensors and samplers was also guided by results of the laboratory convective tank experiments and computer simulations. The distance range of most-needed X measurements was associated with travel times of about 0.3 to 1.2 z_i/w^*. As $\bar{u}z_i/w^*$ was typically 1 to 2.5 km during CONDORS runs, the most desired distances of plume measurements ranged from 0.3 to 3 km downwind of the source. The radar is capable of detecting chaff at much greater distances than this, and the reflected signal is not attenuated by travel back through the plume. Consequently, the radar was sited upwind of the BAO tower, 3.5 km to the east, to reduce the azimuth and elevation angles needed to encompass the plume and to reduce the dynamic range of returns due to $1/r^2$ attenuation. While the radar scans horizontally, the lidar scans in vertical planes, and the signal is attenuated appreciably by travel through the plume. Therefore, it was necessary to site the lidar as close to perpendicular to the plume axis as possible, at a distance minimalizing the elevation angle range needed but without too much signal attenuation. The lidar was sited 3 km from the BAO tower at 325° azimuth in 1982 and was moved to 4 km away at 346° azimuth in 1983, in anticipation of more frequent southeasterly winds (which proved to be the case).

Only one sampling arc could be operated within the available budget. The sampling arc consisted of 29 samplers placed every 5° of azimuth from 202.5° to 342.5°, mostly along roads. This arrangement provided adequate angular resolution for the time-averaged plumes, which were 30° to 90° wide at the arc distance. The midpoint of the arc was 1.2 km to the west of the tower, a good distance for intercepting nearly maximum surface X from the elevated release in almost every case.

Tracers and Sensors

The primary mapping of plume concentration fields was done by the two remote sensors, radar mapping chaff and lidar mapping oil fog. These techniques were supplemented by conventional sampling and gas chromatography analysis of plumes containing conservative tracer gases. Each of these three techniques has some areas of advantage as well as some substantial limitations.

Lidar is a well-proven tool for mapping atmospheric aerosol fields and light-reflecting plumes. The WPL lidar uses a frequency-doubled Nd:YAG laser transmitter firing at 10 pulses/s. It is easily able to map atmospheric haze cross sections several km deep; this capability was valuable for making quick estimates of z_i during CONDORS runs. Oil fog was used as a tracer because of the economics of producing enough plume particles to make the plume distinguishable from atmospheric haze after dilution with roughly 10^7 m^3/s of air. In the commercially built oil fogger used in CONDORS, oil is sprayed into a heated jet of air, causing it to vaporize. On mixing with ambient air, it cools and condenses into drops a few microns in diameter which are very efficient reflectors of laser light. In 1982, a pale paraffin type oil was used, which was not expected to significantly evaporate as it travelled downwind; however, the decline of integrated return signal from larger x scans suggested otherwise. The maximum x of plume distinguishable from ambient haze was only 1.9 km, short of the experimental goal. To improve this range to 2.9 km, in 1983 a heavier oil was used; this change required modification of the fogger to preheat the oil to reduce its viscosity. In addition, a second oil fogger was operated during surface releases; however, it could not be accommodated on the tower carriage for elevated releases.

The energy of each pulse and the digitized photomultiplier detector signal were recorded for later processing. Just prior to each run, about six azimuths were chosen for lidar scanning, which was controlled by computer. Each scan at an azimuth contained about 100 pulses, beginning at a maximum elevation angle that fully encompassed the plume. The scans had to be terminated a few tens of meters above the surface because the laser beam was not eye-safe. The scan at each azimuth was repeated approximately every 210 seconds throughout the runs, so that ensemble-averaged plume X could be obtained. The spatial resolution of the lidar was of the order of a few meters, which was more than adequate.

Post-experiment lildar signal processing for CONDORS achieved new levels of quantification of plume returns in terms of concentration fields. This required considerable computer processing time and man-machine interaction, as each averaged scan had to be corrected for attenuation of the signal by travel through both background haze and the plume itself. Because the oil fog droplet size distribution was unknown, only the relative concentration field at each azimuth of scan could be determined. Consequently, to estimate X/Q for a conservative tracer, where Q is the release rate, Q was replaced by the measured downwind flux of relative X ($\bar{u}$ times $\iint X dydz$, where y is the lateral dimension). This expedient assumes that the droplet size distribution and the percentage evaporation is constant across each scan section.

In recent years, radar has been used to map clear airflow structures using a tracer called "chaff," aluminum-coated mylar threads. During CONDORS, bundles of these threads were unwound from reels, chopped into 1.6-cm lengths, and ejected by an air jet at the rate of 38,000 filaments/s by a "chaff cutter." The majority of the filaments clump together and quickly fall to the ground, but enough single filaments are produced to provide very reflective targets for WPL's 3.2-cm wavelength Doppler radar. At typical CONDORS ranges, the radar could easily detect one filament in a $(50\ m)^3$ volume of air. Acquisition of signal was limited to $x \simeq 3.5$ km because of the experimental focus and high data processing costs. The chaff volume was too small to be seen by the lidar, and oil fog droplets are extremely poor reflectors of X-band electromagnetic waves, so the two remote sensor/tracer systems were quite independent.

Chaff used as a tracer has one significant drawback, namely, a settling speed of about 0.3 m/s. Convective turbulence has vigorous upcurrents of 1 m/s and more, so chaff is easily mixed up through the whole mixing layer, but it does not distribute exactly as a passive, non-buoyant tracer (oil fog droplets are small enough to have negligible settling speed). This is the main reason that collocated releases of chaff and oil fog were made, to gauge this behavior. It was decided to use chaff only for elevated releases in 1983 because it is relatively easy to correct the distribution for settling speed effect before surface contact occurs; comparisons of plumes from collocated oil fog and chaff releases showed the expected magnitudes of downward displacement of chaff $\bar{z}$ (mean height). More sophisticated correcton schemes can be applied near the point of maximum surface impact, but this is not done in the CONDORS data report. At farther distances downwind, chaff deposition and resuspension become additional complicating factors which may frustrate attempts to correct for settling effects.

The X-band Doppler radar used in CONDORS has a beam width of 0.8° and a pulse volume 90 m deep. Typically, the radar swept horizontally through 1.2° of azimuth during the dwell time (the time of accumulation of sufficient return signal). These factors plus distance determined the typical spatial resolutions for radar scans: 90 m downwind; 70 m vertical; and 160 m crosswind. The radar swept through enough azimuth to encompass the plume to at lease x = 4 km and was raised vertically by about 0.7° increments to encompass the depth of the plume, repeating the whole sequence about every 135 seconds. The data for selected averaging periods were later processed and interpolated into Cartesian coordinates with $(50\ m)^3$ cells. Most ground clutter (strong reflections due to surface objects) was avoided by purposely siting the radar so that nearby terrain blocked the beam below about 0.5° above horizontal. This also caused loss of signal from plume concentrations near the ground. Remaining clutter that was stationary was mapped by the radar when the chaff was absent (some clutter due to aircraft and surface vehicles had to be removed at program operator discretion). In the affected cells, the signal was kept only if it was at least 10 db (a factor of 10) stronger than the mapped ground clutter, or if it showed a doppler speed above a value set for each averaging period, using the fact that uncontaminated plume returns have speeds near $\bar{u}$.

Chaff could not be considered a conservative tracer because of the large dropout of chaff clumps in the first few hundred meters downwind and significant surface deposition after the point of ground contact (in some runs, the integrated plume signal, $\iint \chi dydz$, declined as much as 50% in the distance interval 1 to 3 km). The estimation of equivalent χ/Q for conservative tracer was done in the same way as for oil fog, by replacing Q with $\bar{u}\iint \chi dydz$ evaluated at each mean downwind distance. This estimate, of course, does not correct for distortion of the vertical concentration profile which is due to deposition loss and settling.

Tracer gas sampling and gas chromatography analysis is a well established method for determining conservative-tracer χ/Q accurately (within about ±10%). During the 1983 CONDORS runs, SF_6 was always released a few meters from the chaff cutter, on the BAO tower carriage. Freon 13B1 (CF_3Br) was released from the surface, a few meters from the oil fog generators when they were also on the ground. The gases were stored in compressed gas cylinders and piped through linearized mass flow meters to the release nozzles, with strip charts recording release rates and digital readouts of total release volume. The release volume reading was checked against before and after weights of the gas cylinders.

Each sampler box contained 12 two-liter sample bags, each with its own pump and intake tubing. A remote switch connected by wire to the line of samplers initiated the sequential 10-minute sampling for each 120-minute run. After each run the sample bags were collected by a person who had not been near the release points, to avoid contamination. The bags from each sampler were labeled and packed into separate 12-compartment boxes for shipment to Idaho Falls for analysis. The samplers were analyzed in the laboratory by use of electron capture gas chromatographs (GCs). Careful check-in and handling procedures were followed, with calibration of the GCs with reference gas mixtures before and after each analysis shift. Repeatability tests and independent audits of reference gas mixtures suggest total errors in measured plume χ/Q of less than 10% for SF_6. However, uncertainty in 13B1 measurements was much greater because plume concentrations were of the same order as the GC threshold noise levels.

Several months after the field work, in spite of many precautions, 3/8 of the SF_6 samples and 7/8 of the 13B1 samples were discovered to be severely contaminated. After many months of investigations it was determined that (1) contrary to instructions, partly filled gas cylinders were returned to Idaho Falls in the same truck compartment with the last three days' samples, (2) that all gas cylinder valves leak to some extent, and (3) that clean sample bags stored in the truck with gas cylinders do become contaminated at the high levels that had been measured (100 to 1000 times expected plume concentrations). Later, it was found that the contaminating gas does not penetrate the bags, but resides on the lead-in tubing attached to the bags. Four days of the remaining 13B1 samples were also contaminated. No proof of cause was discovered, but the bags probably were stored near some leaky gas cylinders at the BAO just prior to use. The remaining five days of SF_6 samples showed no evidence of contamination except for occasional "spikes" of high concentrations at individual samplers, sometimes recurring several times among the 12 sequential samples from a run. This spiking occurred in about 3% of the SF_6 samples and remains unexplained.

Meteorological Measurements

As for any diffusion field experiment, good meteorological measurements were vital to the success of CONDORS, both from the operational and the scientific analysis viewpoints. It was particularly helpful to go beyond the limitations of past field experiments in measurement of variables important to convective turbulence and diffusion, especially z_i and w^*. The BAO meteorological tower provided an excellent starting point. It is equipped with three-component sonic anemometers, propeller vanes, platinum wire and quartz thermometers, and dew point hydrometers at eight levels: 10, 22, 50, 100,150, 200, 250, and 300 m AGL. It has been operated more-or-less continuously since 1980 with real-time logging of 20-minute averages, including variances and covariances of wind speed components and temperature. During CONDORS runs, the tower data were logged in fast response modes so that many types of statistical analyses could be made at a later date. For instance, immediately after the experiments, 5-minute averages of wind speeds, directions, and $\overline{w'T'}$ were calculated to help define optimum averaging periods that avoid large changes in these variables. To reduce bulk, much detailed statistical information for the selected 1983 averaging periods was processed but not included in the data report, including moments of vertical velocity ($\overline{w}, \overline{w^2}$, and $\overline{w^3}$), individual and joint distributions of 10-seconds average horizontal and vertical wind directions (θ_a and θ_e), and $\bar{u}$, $\bar{\theta}_a$, and θ_a distributions conditionally sampled during negative 10-seconds $\bar{w}$ events.

While the tower provided quite detailed meteorological information for the lowest 300 m, the experiment required some information up to $z = z_i$ and somewhat beyond. This was provided mostly by rawinsondes, which were released near sunrise and at least twice during each run. In 1983, a release near 1000 MST was added to help track z_i development and to check upper level winds for possible changes in expected midday winds in the mixing layer (as z_i grows, momentum from the entrained air is mixed downward). The rawinsondes were tracked by double theodolite to about 3000 m AGL so that wind speed and direction profiles, as well as temperature and humidity profiles, were obtained. Additional meteorological information included solar insolation at the surface and acoustic sounder records.

A summary of important meteorological and source information for each averaging period is given in Table 1. Periods were numbered separately in the 1982 and 1983 experiments. Start times were Mountain Standard (MST), which was, fortuitously, extremely close to true solar time at the BAO. Averaging period durations were usually 30 to 50 minutes, limited by rapid changes in wind or z_i or, in a few cases, by breaks in chaff or oil fog releases. For convective experiments, the most critical measurement is the mixing depth, z_i. For 1982 periods, this was determined entirely from the chaff $\int \chi dy$ profiles at $x > 2$ km by a "zero projection" method. Oil fog detection did not extend far enough in 1982, but this method was applied to 1983 oil fog $\int \chi dy$ profiles. A second method using $\int \chi dy$ vertical profiles of oil fog and chaff was also used in 1983; it set z_i as the height of dropoff to 40% of a peak or plateau value in the upper half of the profiles. Rawinsonde measurements of virtual potential temperature, dew point, and wind velocity profiles and lidar measurements of haze dropoff heights provided additional indicators of z_i. Using a consensus of these estimates, the accuracy of the 1983 z_i estimates is thought to be ±20 m to ±50 m. The convective scale velocity (w^*) depends only on the 1/3 power of z_i and $\overline{w'T'}$. The latter quantity was taken as the average of the 10- and 22-m level tower measurements; at higher levels it tended to be erratic. The mean wind speed and direction ($\bar{u}$ and $\bar{\theta}_a$) were taken as the average of the upper four levels of sonic anemometer measurements. Based on past meteorological experiments, this is believed to represent well the whole mixing layer from 0.1 to 0.9 z_i (wind velocity shear was very slight or negligible above 100 m during CONDORS runs).

An underlined release height for oil fog or chaff in Table 1 indicates that the remote sensor data were processed for that period. SF_6 heights are listed only for uncontaminated periods; 13B1 χ/Q is available only for period 1-83. The last column shows the ratio of source height (z_s) to z_i for the elevated release, if there was one. The post-experiment estimates of z_i show that the experimental targets of $z_s/z_i \simeq 1/4$ or 1/2 were usually missed. However, the groupings of periods near $z_s/z_i = 0.17, 0.33$, and 0.43 make possible the combination of periods to achieve better ensemble averaging for elevated sources. For surface sources, data from all periods can be combined in terms of the dimensionless convective scaling coordinates z/z_i, y/z_i, and $X = (x/\bar{u})w^*/z_i$. Weighting of the periods can be done using absolute duration or durations normalized by $z_i/\bar{u}$, which typifies the passage time of individual convective eddies.

Data Reported

Although the final report gives detailed explanations of the CONDORS experiment planning, siting, instrumentation, operating procedures and processing methodologies, it is primarily a data report. Consequently, the bulk of the final report consists of tables and figures—approximately 230 tables and 240 figures. This quantity of information can hardly be summarized, but a reasonably complete

Table 1. *Meteorological Measurements and Source Summaries for CONDORS Averaging Periods*

Period Number	Month/ Day	Start Time	Duration (min)	z_i (m)	w^* (m/s)	$\bar{u}$ (m/s)	$\bar{\theta}_a$ (deg)	$\overline{w'T'}$ (m°C/s)	Source Height (m) Oil	Chaff	SF_6	z_s/z_i
0-82	9/10	1143	36	1000	2.07	3.65	114	0.271	sfc	sfc	---	---
1-82	9/16	1304	29	520	1.46	5.80	52	0.186	235	235	---	0.45
2-82	9/16	1411	35	730	1.43	6.23	50	0.124	235	235	---	0.32
3-82	9/18	1354	40	960	1.54	2.76	89	0.117	167	167	---	0.17
4-82	9/20	1153	44	980	1.81	2.40	52	0.186	sfc	sfc	---	---
5-82	9/20	1312	42	1260	1.82	1.59	59	0.148	sfc	sfc	---	---
1-83	8/27	1330	30	1600	2.00	3.15	121	0.158	sfc	265	265	0.17
2-83	8/28	1130	30	1240	2.01	1.91	117	0.207	sfc	235	235	0.19
3-83	8/28	1230	60	1400	1.99	2.57	107	0.179	sfc	235	235	0.17
4-83	8/31	1055	50	1100	1.88	1.90	127	0.189	sfc	280	280	0.25
5-83	9/06	1050	40	880	1.64	2.52	122	0.152	280	280	280	0.32
6-83	9/06	1130	30	880	1.74	2.59	140	0.184	280	280	280	0.32
7-83	9/06	1210	30	880	1.65	3.34	122	0.158	280	280	280	0.41
8-83	9/07	1230	40	640	1.38	4.45	91	0.130	265	265	265	0.41
9-83	9/07	1310	40	780	1.48	4.59	87	0.133	265	265	265	0.34
10-83	9/13	1140	30	900	1.80	2.09	102	0.200	sfc	235	---	0.26
11-83	9/13	1240	40	870	1.86	1.57	56	0.227	sfc	235	---	0.27

description of it can be given. This description will be done in the following order, representing an increasing amount of informational detail reported: meteorological parameters, gaseous tracers, chaff, and oil fog.

The basic meteorological parameters reported for each averaging period have been repeated in this project summary in Table 1, except for the derived parameters $\bar{u}/w^*$ (shows degree of convectiveness), $z_i\bar{u}/w^*$ (length scale for transport distance), and period duration times $\bar{u}/z_i$ (dimensionless duration in terms of "eddy passage time"). Detailed listings of 1983 z_i estimates are given in the final report to show the consistency of differing methods; the nine types of estimates never all agree, but, in each period, at least several methods give approximately the same value. Finally, some examples of the statistical information available for 1983 periods are given, namely, actual distributions of 10-s average wind azimuth and elevation angles, by 5° bins, for z = 250 m. Most of the azimuth distributions are approximately Gaussian, but most elevation angle distributions are skewed strongly toward negative values. Much more statistical information was processed but was too bulky to be included; the same is true of the 5-minute averaged tower measurements and the rawinsonde profiles.

Essentially all of the processed results of the 1983 gaseous tracer sampling, except for the highly contaminated runs, are included in the final data report. Basic information includes the range and azimuth of each sampler from the center of the BAO tower and the average release rate(s) of the two gases for each usable run. The rest of the information concerns measured X/Q values, the ratio of concentration to release rate. In the final report tables are given for every 10-minute sample of X/Q at each sampler for each entire two-hour run that was not contaminated (one run for 13B1, five runs for SF_6). However, a small fraction of such samples are missing due to sampler inoperation. Two tables of averaged X/Q for the chosen averaging periods are presented: one with all the available 10-minute averages and one with "spikes" of anomalously large X/Q values removed. These spikes are identified in two tables, one listing multiple spikes at a single sampler (exceeding both background and the averaged two neighboring samplers by at least a factor of 5) and one listing especially large single spikes (exceeding both background and the averaged two neighboring samplers by at least a factor of 10). A figure is shown for the frequency of occurrence of X/Q values during each run; this was used to set "background," or noise level, values. There are also figures for each usable 1983 averaging period showing average X/Q values, both with and without spikes, versus azimuth position of the samplers.

The basic information for the radar/chaff results includes the Cartesian grid range and increment chosen in processing each period, the direction chosen for the x-axis, and the velocity chosen for thresholding out return signals contaminated with ground clutter. Then chaff plume statistics are presented in tables for each processed averaging period as functions of $\bar{x}$, mean distance downwind, incremented by 250 m or 300 m. Statistics include $\bar{y}$ and $\bar{z}$, σ_y and σ_z (standard deviations), the y of maximum $\int X dz$ and the z of maximum $\int X dy$, the value of maximum $\int X dy$, and $\iint X dz$. An appendix to the final report shows plots of each of these quantities (except $\bar{y}$) versus x in 50-m increments. It also shows normalized $\int X dy$ or $\int X dz$ versus z or versus y and versus $\bar{x}$, in semi-tabular form, for each processed averaging period; $\bar{x}$ is usually in 250-m increments. Finally, a time history of the contour $\int X dz$ = 100 filaments/(50 m)^2 versus x and y is shown for selected periods from 1983.

The basic information presented for the lidar/oil fog results, besides specifics on the lidar and laser beam, consists of logs of release and scan periods. Then oil fog statistics for each lidar azimuth are presented for each processed averaging period. Statistics include the mean distances from the source and from the tower base (when used as a surface source, oil fog was released 134 m west and 44 m north of the tower), the corresponding mean azimuth angles, σ_y projected on the y-axis, σ_z, $\bar{z}$, z of maximum $\int X dy$, a calibration factor proportional to $\iint X dydz$, and the acute angle between the lidar azimuth and the perpendicular to the plume axis. An appendix to the final report contains about 100 tables and 100 figures showing normalized values of $\int X dy$ and $\int X dz$ for each scan of each processed period. These values are given with 50-m horizontal and vertical resolutions; in addition, for some scans close to the oil fog source, these are given with 25-m and even 12.5-m resolutions. The figures also show X versus range and height for each scan, using symbols with graduated degrees of darkness for ranges of increasing X. A final set of about 80 tables in the appendix shows inferred values of X/Q versus azimuth angle from the source for the lowest data-complete layer in each processed scan; these are the best estimates of surface concentration derivable without extrapolation from the lidar scans of oil fog.

Conclusions

Because this project report is primarily a data report, most of the conclusions concern how well the data obtained met the experimental goals. However, from preliminary scientific analyses of the data presented at conferences, and some further analyses presented in the final project report, some tentative conclusions can be made about convectively-driven diffusion in the field (much more extensive analyses are in preparation for publication in scientific journals). The tentative conclusions concerning the data quality are as follows:

Overall. The experiment was carried out with the targeted number of runs and with acceptable meteorological conditions in both years of the project. Four trial runs were made in 1982 and eight runs with all systems operating were made in 1983. Except for 62% of the gaseous tracer samples found to be contaminated and not usable, all data acquisition was successful.

Meteorological Data. The meteorological data acquired were more than adequate to meet the experimental goals. There was much redundancy, with nine different indicators of z_i and eight levels of wind and turbulence measurements. Much more wind statistical information was processed than has been available in past diffusion experiments.

Radar and Chaff. Both the radar and the chaff source functioned well, with only a few sort lapses of several minutes. Ground clutter was successfully eliminated from the processed returns, but part of the plum signal in the lowest 60 or 110 m was also lost (110 m at larger x, especially in the SW sector). The expected magnitude of downward drift due to chaff settling speed was seen in direct comparisons of chaff and oil fog $\int X dy$ distributions. Settling speed effects can largely be accounted for up to the distance of maximum surface impact from an elevated chaff source, but deposition and resuspension further complicate matters beyond this point. The radar provided very good coverage of the plume in three dimensions, but with somewhat limited resolution.

Lidar and Oil Fog. Both the lidar and the oil foggers performed well, with only a few very short lapses. A large release rate was required to produce a plume that could be distinguished from background haze at 2 to 3 km downwind in convective conditions. This goal was marginally achieved in 1983 by switching to a very heavy oil and adding a second fogger for the surface releases. The paraffin type oil used in 1982 apparently evaporated to a significant degree. The lidar provided very good resolution of plume scans, but with limited coverage of azimuths.

Samplers and Gases. The single sampling arc with 5° azimuth spacing provided adequate "ground truth" in this experiment to test the X/Q assumptions applied to the observed distributions of chaff and oil fog, which are not conservative tracers. The loss of more than half the data due to contamination was unfortunate and avoidable, in retrospect. Sample bags should not have been stored near source gas cylinders, especially in an enclosed space, because the common type of cylinder valves do leak slightly. The contaminated samples could have been saved had the discovery been made in time that the contaminating gases resided only on the intake tubing, not *inside* the bags. At any rate, the 13B1 gas released from the surface was inadequate because the concentrations at the sampling arc were of the same magnitude as the QC threshold noise levels. The SF_6 gas released from the tower was adequate and provided five runs of useful data.

Tracer Comparisons. As already mentioned, with collocated releases the chaff plumes generally tended to sink lower than the oil fog plumes, to the expected degree, due to gravitational settling. However, the horizontal patterns of $\int X dz$ tended to agree very well. Several literature references also compared SF_6 with the lowest layer oil fog X/Q at the azimuth nearest the sampling arc for period 9-83, finding disagreement on the location of plume boundaries and peak by only about 1° of azimuth, or 20 m. The $\int (X/Q) dy$ of the oil fog was only 16% larger than that of SF_6; this is very satisfactory considering the difference in methods and the inexact coincidence in space.

Preliminary and partial analysis of selected periods from both 1982 and 1983 lead to the following tentative conclusions about diffusion in convective conditions (WD stands for the convective tank experiments of Willis and Deardorff):

Plume Width and Depth. The final data report shows that σ_z/z_i vs. $X = (x/\bar{u})w^*/z_i$ for period 9-83 (an example) is in very good agreement with WD for both oil fog and chaff measurements. On the other hand, σ_y/z_i vs. X is in good agreement with WD for some periods and is about twice as large in others identified as having unusually large wind direction shears for CBLs. The large wind shears may be a site anomaly due to the proximity of the Rocky Mountains.

Qualitative Behaviors of $\int X dy$ vs. x and z. The figures in the final report's appendix showing oil fog profiles for each scan azimuth offer the best overview of plume behavior in the vertical dimension, because the periods are evenly split between elevated and surface releases and there are no settling effects of concern. For the eight averaging periods with surface releases, the maximum in $\int X dy$ profile lifts off the ground in every case (quick calculations show that this occurs roughly near $X \simeq 0.5$, in agreement with WD). The maximum lofts to the upper half of the mixing layer in the scans at largest x during five periods, but remains somewhat lower in the other three periods. For the eight elevated release periods, in two of these, the diffusion somewhat resembles the conventional Gaussian plume. In the other six, the $\int X dy$ maximum does descend to the surface, although in half of such cases it rises slightly before making a rapid descent. (Quick calculations show that the maximum surface impacts are in the neighborhood of $(x/\bar{u})w^*/z_s \simeq 1.5$ to 3, which, again, roughly agrees with the literature references.)

Quantitative $\int X dy$ Behaviors. Some limited analyses have been done on normalized values of $\int X dy$, or $C_y = \overline{u z_i} \int X dy/Q$, measured during CONDORS. A 1983 literature reference showed C_y contours vs. X and $Z = z/z_i$ for chaff in period 1-82. Except for more "lumpiness," these contours bear striking resemblence to WD results for $z_s/z_i = 1/4$, up to the limits of measurement at X = 1.7. Oil fog C_y for period 5-83 also showed close agreement with WD at scans corresponding to X = 0.25, 0.51, and 0.87. The oil fog in period 9-83 tended to ascend slightly at small X, but at X = 0.46 the maximum C_y was at the surface and agreed quite well with WD. The chaff C_y in the same period was more like a Gaussian plume at $X \leq 0.24$ and at X = 0.43, but was in fairly good agreement with the WD descending plume behavior at X = 0.34 and 0.72.

We conclude for now that the vertical behaviors of diffusion in this field experiment were much like the behaviors observed in the laboratory tank by Willis and Deardorff and calculated in computer simulations by Lamb, except that more variability is seen in the field experiment results. This is not too surprising, as averaging times in the field represented a smaller "ensemble" of eddies and the real world is not so ideal.

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The complete report, entitled "Project CONDORS—Convective Diffusion Observed by Remote Sensors," (Order No. PB 86-222 221/AS; Cost: $28.95, subject to change) will be available only from:
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