17th International Conference on
Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes
9-12 May 2016, Budapest, Hungary

PROJECT SAGEBRUSH: A NEW LOOK AT PLUME DISPERSION

Kirk L. Clawson, Richard M. Eckman, Dennis D. Finn

National Oceanic and Atmospheric Administration (NOAA), Air Resources Laboratory,
Field Research Division, Idaho Falls, Idaho USA

Abstract: Project Sagebrush (PSB) is a multi-year tracer dispersion field experiment based roughly on the venerable Project Prairie Grass (PPG) conducted in 1956. PSB builds on and expands the results of PPG and other early dispersion tests through the use of modern 3-d sonic anemometers to directly measure atmospheric turbulence and through the use of fast-response analyzers for measuring tracer concentration fluctuations. The first phase of Project Sagebrush (PSB1) was conducted in October 2013. A total of 5 tests were completed resulting in 60 separate sample periods. One hundred-fifty bag samplers were used to obtain ten-minute average concentrations while six real-time analyzers simultaneously sampled tracer concentration fluctuations. A bevy of meteorological instruments was also utilized. Examination of cross-wind concentration fields showed that PSB2 plumes were generally more spread out and much less Gaussian in shape than plumes from PPG. The data from PSB1 are openly available for further scientific scrutiny and model testing. A follow-on study dubbed PSB Phase 2 will be conducted in 2016 with a focus on light wind speed conditions.

Key words: *Atmospheric tracer dispersion, field studies, atmospheric stability, atmospheric turbulence, Project Prairie Grass*

INTRODUCTION

The benchmark tracer dispersion studies of the 1950s and 1960s are still the basis for modern dispersion model development and validation [e.g., AERMOD (Cimorelli et al. 2004), RLINE (Snyder et al. 2013), and ADMS (Carruthers et al. 1994)]. Those early dispersion studies were carefully designed to take advantage of the latest meteorological and tracer measurement technology available at the time. Project Prairie Grass (Barad, 1958), conducted in 1956 in the state of Nebraska, USA, is perhaps the best known of these classic experiments. Project Prairie Grass (PPG) was focused on short-range dispersion from a near-surface source over flat terrain.

Although PPG remains one of the most used dispersion studies in flat terrain, many users are unaware of its limitations. For example, sulphur dioxide (SO_2) was used as the tracer gas in PPG; it is both reactive and depositing, and these characteristics may affect the interpretation of the results. Furthermore, estimates of atmospheric boundary layer stability and surface fluxes were derived from mean wind and air temperature profiles because the ability to measure fluxes directly was severely limited. Information on vertical dispersion came from a single set of towers 100 m downwind of the source, with a maximum tracer measurement height of 17.5 m AGL.

Over the course of the last half century, there has been considerable improvement in both meteorological and tracer measurement technologies. Now it is possible to measure three-dimensional atmospheric turbulence directly with high fidelity–a capability that did not exist when PPG was conducted. Likewise, tracer concentration fluctuations can now be measured. The arrival of these new technologies has led some experts to recommend that the early dispersion experiments be reinvestigated using the new tools that are now available. Further impetus for new tracer studies comes from a 2008 tracer experiment conducted at the Idaho National Laboratory (Finn et al., 2010). This experiment focused on the effects of roadside sound barriers on vehicle pollution, but a subset of the data was compared to PPG results and showed interesting deviations (Venkatram, 2011, personal communication).

Because of these developments, the Field Research Division (FRD) of the National Oceanic and Atmospheric Administration Air Resources Laboratory (NOAA ARL) has begun a new series of tracer experiments using modern turbulence instrumentation and tracer technology. The experiments are collectively called Project Sagebrush (PSB) in a nod to its predecessor, Project Prairie Grass. PSB is a multi-year dispersion study that is being based loosely on PPG with a continued focus on short-range dispersion in open terrain.

NOAA GRID 3 TRACER DISPERSION TEST BED

Project Sagebrush is being conducted at the NOAA Grid 3 tracer dispersion test bed (Grid 3) on the Idaho National Laboratory (INL), a U.S. Department of Energy facility in southeast Idaho, USA. The INL covers approximately 2,300 km^2 and is located in a broad, relatively flat plain on the western edge of the Eastern Snake River Plain (ESRP). The average elevation across the INL is approximately 1500 m MSL. Several parallel mountain chains with peaks exceeding 3000 m MSL dominate the western edge of the ESRP. These chains are separated by a series of tributary valleys that feed into the ESRP. The base of the closest mountain peak is approximately 15 km from the Grid 3 facility.

Grid 3 was first used in the late 1950s or early 1960s for tracer dispersion studies. Sampling arcs have been surveyed at 25, 50, 100, 200, 400, 800, 1600, and 3200 m. Conducting PSB at Grid 3 allows ARLFRD scientists to use valuable knowledge gained from previous work [e.g., Start, et al. (1984), Sagendorf and Dickson (1974), Garodz and Clawson (1991, 1993), and Finn et al. (2010)]. Grid 3 is well-positioned near the middle of an existing 34-station mesonet that was designed for the very purpose of collecting high fidelity wind data required for emergency dispersion modelling to support the safe operation of INL research nuclear reactors and associated activities (Clawson et al. 2007; Rich et al. 2016).

An important feature of Grid 3 is a 62 m tower (designated GRI) that provides vertical profiles of wind and air temperature. Soil moisture and temperature are also measured at 5 depths at GRI. A 924 MHz wind profiling radar with RASS and a mini-SoDAR are also permanently installed at Grid 3. The radar measures wind profiles in 100 m increments up to 2.9 km and virtual temperature profiles up to 1.0 km AGL. The SoDAR measures winds in 10 m increments up to 200 m AGL. An Eddy covariance surface flux system has been in operation at Grid 3 since 2000 for the measurement of sensible heat, latent heat, soil heat, and momentum fluxes and for the measurement of the complete energy balance.

Grid 3 offers relatively uniform aerodynamic characteristics across the study area. The canopy is mostly sagebrush and grass. The near-surface wind usually blows parallel to the axis of the ESRP, with southwest winds common during the day and northeast winds at night (Clawson et al. 2007). The median roughness length (z_o) has been determined to be 3-4 cm. The displacement height (d) estimate was not significantly different from 0. The orientation of the prevailing winds means that the tracer facility has a relatively flat, uniform fetch extending many tens of kilometers in the prevailing upwind direction.

PHASE 1 EXPERIMENTAL DESIGN

Phase 1 of Project Sagebrush (PSB1) utilized all of the meteorological equipment described above, and added a suite of additional atmospheric turbulence measurements to fully describe and identify the meteorological factors controlling tracer dispersion. An array of tracer sampling equipment was also deployed that included real-time analyzers as well as bag samplers. Full details of the experiment can be found in the data report by Finn et al. (2015).

Additional Meteorological Equipment

The following broad array of meteorological instrumentation was deployed at Grid3 in addition to the existing instrumentation:

- 62 m tower (GRI): 3-d sonic anemometers at 7 levels; 2-d sonic anemometers at 6 levels; air temperature and relative humidity at 14 levels; fast response infrared gas analyzers at 4 levels; solar radiation, barometric pressure at 3 levels; net radiometer at 2 levels; infrared thermometer, soil heat flux at 2 levels.
- Three 3-d sonic anemometers arrayed along the 3200 m arc (R2, R3, R4).

- 10 m meteorological tower at 3200 m (TOW): cup and vane anemometers at 2 levels.
- 30 m Command Center (COC) meteorological tower: cup and vane anemometers at 3 levels.
- 1 additional SoDAR at 3200 m arc (wind profiles from 30-200 m).
- Radiosonde launches before and after each test.

Tracer Sampling Strategy

Six fast response SF_6 analyzers were deployed to measure concentration fluctuations. Five of these were mounted in vehicles and co-located with a bag sampler on the sampling arcs. One analyzer was mounted in an airplane provided by the University of Tennessee Space Institute during tests 1, 2, and 3. During tests 4 and 5 the airplane was not available, so this analyzer was re-located to a site on the sampling arcs.

Tracer releases were restricted to the daytime when prevailing winds were from the southwest. Therefore, the study domain was located on the northeast quadrant of the Grid 3 dispersion test bed. Twenty-eight bag samplers were placed at 3º intervals from 4º azimuth to 85º azimuth along each of the 4 circular arcs designated for a test. These were either the 200, 400, 800, and 1600 m arcs or the 400, 800, 1600, and 3200 m arcs, depending upon the forecast atmospheric stability and the planned release rate. Each bag sampler was mounted at 1 m AGL and contained 12 bags. The 12 bags collected samples sequentially with each bag covering a 10-minute interval, so concentration averaging times between 10 minutes and 2 hours are available at each location.

Three towers were available for vertical tracer sampling to the northeast of the source. Four samplers were mounted on a 15 m tower (1, 5, 10, and 15 m AGL) located at the intersection between the 55º azimuth radial road and the 200 m arc. Five samplers were mounted on a 21 m tower (1, 5, 10, 15, and 20 m AGL) located at the intersection of the radial road and the 400 m arc. Seven samplers were mounted on a 30 m tower (1, 5, 10, 15, 20, 25, and 30 m AGL) located 499 m from the source at about 60º azimuth. This tower served the dual purpose as the meteorological tower for the nearby command center (COC). A total of 150 bag samplers, including those used for quality control, were employed during each test.

Tracer Release Strategy

Five sulfur hexafluoride (SF_6) tracer releases took place from 02 October to 18 October, 2013. SF_6 has several advantages over SO_2 (the tracer used in PPG) because it is non-depositing, non-reacting, and non-toxic. It is also odorless, and invisible. SF_6 tracer was released continuously at a constant rate from a point source at 1.5 m AGL at the center of the dispersion array for each test. The releases began one-half hour prior to the start of sampling on the dispersion array to establish a quasi-steady state SF_6 plume across all of the arcs. The release then continued for the two-hour sampling duration in each test. Release rates were set based upon preliminary estimates of concentrations at different heights and distances, the anticipated atmospheric stability conditions, and whether the aircraft would be making tracer measurements.

RESULTS AND DISCUSSION

A brief summary of test dates and times, tracer release rates, general meteorological conditions, and atmospheric stability is listed in Table 1. Since all tests were conducted in the afternoon, atmospheric stability ranged from unstable to neutral. A total of 60 unique tracer sample periods were collected.

Table 1. PSB1 test summary. σ_θ is the standard deviation of the wind direction.

Test	Date	Start Time (MST)	Release Rate (g s^{-1})	Meteorological Summary	Atmospheric Stability
1	02 Oct 2013	1430	10.177	Mostly sunny with cirrostratus haze. Wind speeds 1-2 m s^{-1}; σ_θ 18-67 deg.	Unstable
2	05 Oct 2013	1300	9.986	Mostly sunny. Wind speeds 2.4-4.8 m s^{-1}; σ_θ 10-64 deg.	Unstable
3	07 Oct 2013	1300	9.930	Mostly sunny. Wind speeds 7.3-10.0 m s^{-1}; σ_θ 8-11.5 deg.	Neutral
4	11 Oct 2013	1400	1.043	Mostly sunny. Wind speeds 4.3-5.9 m s^{-1}; σ_θ 9.5-20 deg.	Weakly Unstable
5	18 Oct 2013	1300	1.030	Mostly sunny. Wind speeds 3.6-5.0 m s^{-1}; σ_θ 11-22 deg.	Weakly Unstable

For the initial analysis, lateral tracer plume spread obtained during PSB1 was first compared with PPG (Aarhus University, 2016). Example graphs are shown in Figure 1. PSB1 plume cross-sections tended to exhibit more complex internal structure and greater variability than PPG cross-sections. With few exceptions, cross-sections deviated significantly from an idealized Gaussian form, mainly during the near-neutral conditions of test 3. Individual cross-sections commonly exhibited irregular concentration variations, outlier peaks, and skewed asymmetry of concentrations around the peak concentration. Furthermore, some of the cross-sections exhibited truncated profiles at the edge of the sampling array. It can also be seen that the PPG plumes exhibited much narrower arcs than the PSB1 plumes for comparable wind speeds and downwind distances.

The plume spread parameter σ_y calculations obtained from PSB1 were compared with σ_y predictions of AERMOD (Cimorelli et al., 2004), a model that uses recent PBL theory to estimate turbulence levels. The values of the empirical constants used in AERMOD are based on fits to PPG data. The comparisons are shown in Figure 2. It is clear the AERMOD predictions do not fit the PSB1 results. These results indicate the need for additional tracer dispersion datasets such as PSB and raise questions about the parameterization and validation of any model that is based upon classical field studies such as PPG.

PROJECT SAGEBRUSH PHASE 2

Project Sagebrush Phase Two (PSB2) will be a follow-on experiment to PSB1 and will focus on light wind speeds ($\leq$2 m s^{-1}) under both stable and unstable atmospheric conditions. Very few data sets with a focus on light winds are currently available for analysis. There were no tests conducted during PPG in light wind conditions, for example. Detailed meteorological measurements similar to those obtained in PSB1 are planned. PSB2 is scheduled to occur this year in two test windows from 25 July to 10 August 2016 and 12 October through 28 October 2016. The first series of tests will be conducted in the afternoon hours and will concentrate on unstable atmospheric conditions. The second set of tests will be conducted in the early morning hours before sunrise and will concentrate on stable atmospheric conditions. Four tracer release periods are planned during each test window, which will result in a total of 96 ten-minute sample periods being available for analysis.

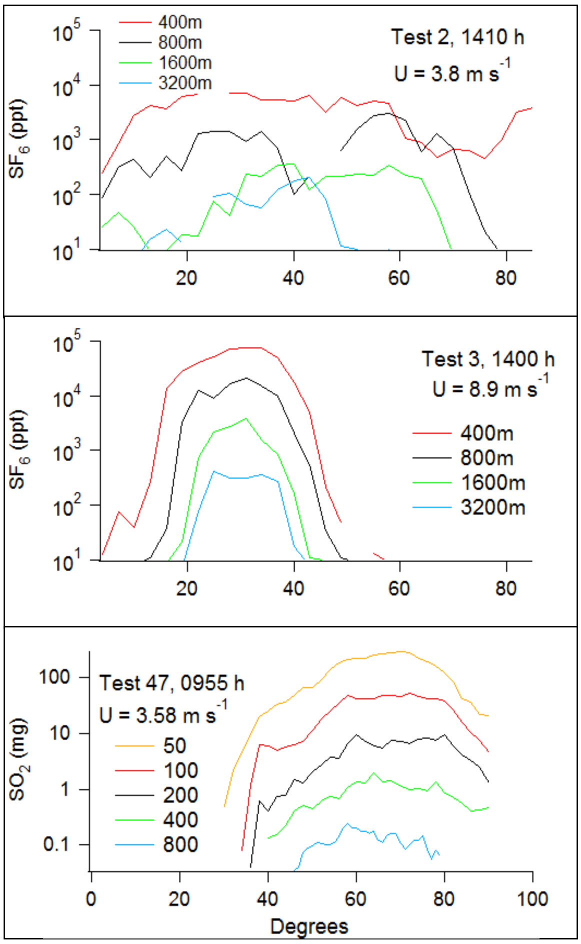

Figure 2. Tracer concentration plume cross-sections from PSB1 Tests 2 and 3 and PPG Test 47.

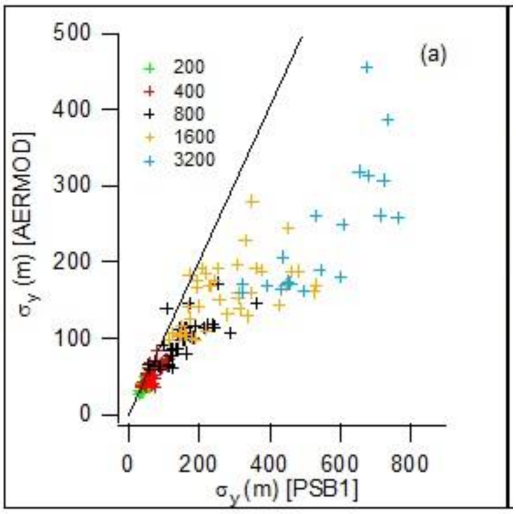

Figure 1. Plots of 10-minute period σ_y predicted by AERMOD versus those estimated from PSB1. The black line is the 1:1 reference.

ACKNOWLEDGEMENTS
We thank Dr. Steve Brooks and the University of Tennessee Space Institute for providing the aircraft. We also thank Dr. Heping Liu, and Messrs. Eric Russell and Zhongming Gao at Washington State University for providing the Eddy correlation equipment and the bulk of the instrumentation on the GRI tower. We are grateful for the entire staff at NOAA ARLFRD and Cherie Clawson for their untiring help with the field work. This work was funded primarily by NOAA annual appropriations.

REFERENCES

Aarhus University, Dept. of Environmental Science, 2015. http://envs.au.dk/en/knowledge/air/models/background/omlprairie/excelprairie/ (accessed 22 Feb 2016)

Barad, M. L. (Ed.), 1958: Project Prairie Grass, a Field Program in Diffusion, Volume I–II of Geophysical Research Papers No. 59. Air Force Cambridge Research Center, AFCRC-TR-58-235, USAF, Bedford, MA, USA.

Carruthers, D. J., R. J. Holroyd, and others, 1994: UK-ADMS: A new approach to modelling dispersion in the earth's atmospheric boundary layer. *J. Wind Eng. Ind. Aerodyn.*, **53**, 139–153.

Cimorelli, A.J., S.G. Perry, A. Venkatram, J.C.Weil, R.J. Paine, R.B. Wilson, R.F. Lee, W.D. Peters, R.W. Brode, and J.O. Paumier, 2004: AERMOD: Description of model formulation. U.S. Environmental Protection Agency, EPA-454/R-03-004, 91 pp.

Clawson, K.L., R.M. Eckman, N.F. Hukari, J.D. Rich, and N.R. Ricks, 2007: Climatography of the Idaho National Laboratory, 3rd edition. NOAA Tech. Memo OAR ARL-259, Air Resources Laboratory, Idaho Falls, ID, USA.

Finn, D., K. L. Clawson, R. G. Carter, J. D. Rich, R. M. Eckman, S. G. Perry, V. Isakov, and D. K. Heist, 2010: Tracer studies to characterize the effects of roadside noise barriers on near-road pollutant dispersion under varying atmospheric stability conditions. *Atmos. Environ.*, **44**, 204–214.

Finn, D., K.L. Clawson, R.M. Eckman, R.G. Carter, J.D. Rich, T.W.Strong, S.A. Beard, B.R. Reese, D. Davis, H. Liu, E. Russell, Z. Gao, S. Brooks, 2015: Project Sagebrush Phase 1. NOAA Tech. Memo OAR ARL-268, NOAA Air Resources Laboratory, Idaho Falls, ID, USA, 338 pp. doi:10.7289/V5VX0DHV

Garodz, L. J., and K. L. Clawson, 1991: Vortex Characteristics of C5A/B, C141B, and C130E aircraft applicable to ATC terminal flight operations, tower fly-by data. NOAA/ERL/ARLFRD, Idaho Falls, ID, USA, 250 pp.

Garodz, L. J., and K. L. Clawson, 1993: Volume 1, Vortex Wake Characteristics of B757-200 and B767-200 Aircraft Using the Tower Fly-By Technique. Volume 2, Appendices. NOAA/ERL/ARLFRD, Idaho Falls, ID, USA.

Rich, J.D., R.G. Carter, K.L. Clawson, D. Finn, 2016: An Overview of the NOAA/INL Mesoscale Meteorological Monitoring Network. Submitted to *Journal of Idaho Academy of Sciences*.

Sagendorf, J. F. and C. R. Dickson, 1974. Diffusion under low windspeed, inversion conditions. NOAA Tech. Memo ERL ARL-52, Air Resources Laboratory, Idaho Falls, ID, USA.

Snyder, M.G., A. Venkatram, D.K. Heist, S.G. Perry, W.B. Petersen, and V. Isakov, 2013: RLINE: A line source dispersion model for near-surface releases. *Atmos. Environ.*, **77**, 748-756.

Start, G. E., J. F. Sagendorf, G. R. Ackermann, J. H. Cate, N. F. Hukari, and C. R. Dickson. 1984. Idaho Field Experiment 1981, Volume II: Measurement data. NUREG/CR-3488 Vol 2, U.S. Nuclear Regulatory Commission.