Appendices

APPENDIX A. HISTORICAL PERSPECTIVE

A.1 Historical Perspective—Meteorological and ATD Modeling

When creating a roadmap for the future, it helps to understand the path that brought us to our present position. The earliest comprehensive effort by a Federal agency to predict the transport and diffusion of airborne particles for public safety purposes began in the 1940s. As the nuclear age emerged, it became apparent that "radioactive fallout was an exceedingly complex issue, involving extremely long range transport through the air and affecting all aspects of the environment."[1]

ATD modeling is generally classified into two subgroups: emergency-response and air quality predictions. Emergency-response forecasting focuses on situations where chemical, biological, or nuclear materials are unexpectedly emitted into the atmosphere and where the source is unknown or poorly described. Air quality forecasting focuses on the U.S. Environmental Protection Agency's (EPA's) criteria pollutants, such as ozone, particulate matter, nitrogen dioxide, carbon monoxide, sulfur dioxide, and lead.

A.1.1 Emergency Response Modeling

In 1948, the U.S. Weather Bureau—the predecessor of today's National Weather Service (NWS) in the National Oceanic and Atmospheric Administration (NOAA), established the Special Projects Section. This office was the forerunner of the Air Resources Laboratory (ARL), now in NOAA's Office of Oceanic and Atmospheric Research. The Special Projects Section was at first funded solely by the Department Of Defense (DOD). Later, it was funded jointly by the DOD and the Atomic Energy Commission (AEC), which was the predecessor of the Nuclear Regulatory Commission (NRC) and portions of the Department of Energy (DOE). The Special Projects Section conducted research related to the U.S. nuclear weapons and atomic energy programs. After a few years, it also provided operational services in support of these programs.

Also in 1948, the U.S. Weather Bureau established and jointly funded with the AEC two research stations at Oak Ridge, Tennessee, and Idaho Falls, Idaho. The Oak Ridge research station was established to study the processes of atmospheric diffusion and understand the dispersion characteristics of the Oak Ridge area. Several other agencies subsequently contributed funds to develop these research facilities into what is now the Atmospheric Turbulence and Diffusion Division of NOAA/ARL.

The AEC and the DOD began joint tests of nuclear weapons in 1951, in the southwest Great Basin, a desert region northwest of Las Vegas, Nevada. A majority of the early tests in this weapons program were atmospheric tests. They showed that a good understanding of the atmospheric environment was necessary to characterize the transport and fallout of airborne radioactive products of the test events. In 1956 the AEC

[1] Excerpted from a historical sketch of the Air Resources Laboratory, on the Internet at www.arl.noaa.gov/history.html.

implemented an Interagency Agreement with the U.S. Weather Bureau to establish a Weather Bureau research station in Las Vegas: the predecessor to the NOAA/ARL Special Operations and Research Division (SORD). The primary function of this research station was to support AEC/DOD test operations by taking local surface and upper air weather observations, preparing weather and trajectory/fallout forecasts, and providing expert meteorological advice to event scientists. These functions continue today, as NOAA/ARL SORD supports DOE's National Nuclear Security Administration (NNSA) at the Nevada Test Site (NTS). By the 1970s, the Field Research Division of ARL, as it is now known, had successfully participated in many experiments, which successfully pioneered the use of tracer technology and data analysis techniques.

In 1973, the DOE Office of Biological and Environmental Research tasked the Atmospheric Sciences Group at Lawrence Livermore National Laboratory (LLNL) to investigate the feasibility of developing an end-to-end, fully integrated system to provide reliable and timely assessment advisories to emergency managers at DOE nuclear facilities in the event of an accidental release of radioactive material to the atmosphere. To characterize the source of the release, this system was designed to rely heavily on downwind measurements and analysis of isotopes. In 1972 the AEC recognized the need for real-time estimates of transport and diffusion (Knox et al. 1981). To meet this need, LLNL developed the Atmosphere Release Advisory Capability (ARAC), which includes an advanced, three-dimensional modeling system of pollutant dispersion and the communications capability to disseminate predictions from this modeling system to local officials (Dickerson and Orphan 1976; Lange 1978; Sherman 1978). A facility to exploit the ARAC, now known as the National Atmospheric Release Advisory Center (NARAC), was officially established in 1979 with funds from a number of agencies, including the DOE. Since its inception, NARAC has responded to a number of accidents including radiological releases at the Three Mile Island nuclear power station in Pennsylvania (Dickerson, Knox, and Orphan 1979) and at the Chernobyl nuclear power station in the USSR in 1986. In 1984, NARAC responded to the atmospheric release of a chemical hazard, methyl isocyanide, at a fertilizer manufacturing plant in Bhopal, India.

Several of the DOE National Laboratories have conducted research in ATD modeling and related research areas. Sandia National Laboratory, for example, has a long of history of source term development for accidents at nuclear power plants. In 2002 the DOE Chemical and Biological National Security Program (CBNP) established the Local Integration of the NARAC with Cities (LINC) program. The CBNP, along with LINC, was transferred to the Department of Homeland Security (DHS) in 2003. The DHS used LINC during the TOPOFF2 exercise in 2003 to demonstrate a capability to provide local government agencies with advanced operational atmospheric plume predictions. NOAA developed a gas and chemical modeling system called CAMEO/ALOHA in 1992 to assist local fire departments in assessing the impacts of accidental releases of hazardous chemicals (NOAA and EPA 1992). ("CAMEO/ALOHA" stands for "Computer-Aided Management of Emergency Operations/Areal Locations of Hazardous Atmospheres.").

DOD was one of the first Federal agencies to fund the development, testing, and application of ATD models. Military interest in ATD modeling originated in the 1940s from a need to quantify the downwind hazards resulting from the use of chemical and biological munitions, including accidental releases of chemical agents at U.S. Army storage depots. With the advent of liquid-fueled rockets in the 1950s, military requirements for ATD modeling expanded to include accidental releases during the transportation, storage, and handling of toxic liquid propellants. Prior to the 1970s, most of the empirical data on ATD came from field studies conducted by DOD organizations such as the Deseret Test Center, Dugway Proving Ground, and Air Force Cambridge Research Laboratory. These field studies included the landmark Prairie Grass (Barad 1958; Haugen 1959) and Ocean Breeze/Dry Gulch (Haugen and Fuquay 1963) experiments. DOD continues to be one of the principal Federal sponsors of ATD field studies, with recent examples including the Mock Urban Setting Test (MUST) (Biltoft 2001) and Joint Urban 2003, which was conducted in collaboration with DHS. During the past 50 years, the Army, Navy, Air Force, and several DOD agencies have developed a series of ATD models to meet specific military requirements. Capabilities from the three major DOD ATD modeling systems are currently being combined into a single Joint Effects Model (JEM) for operational use by all services.

The mandate of the Defense Threat Reduction Agency (DTRA) is to safeguard America's interests from weapons of mass destruction (chemical, biological, radiological, nuclear, and high explosives) by controlling and reducing the threat and providing quality tools and services for the warfighter. DTRA was created in 1998 as the successor to the Defense Special Weapons Agency, which in turn succeeded the Defense Nuclear Agency (DNA) in 1996.[2] In 1996, DTRA developed the Hazard Prediction and Assessment Capability (HPAC) modeling system to calculate the effects of releases of biological, chemical, and nuclear agents. The HPAC modeling systems uses SCIPUFF, a Lagrangian puff model, to simulate transport and diffusion (Sykes et al. 1996).

A.1.2 Air Quality Modeling

In 1955, in response to a request from the Air Pollution Unit of the U.S. Public Health Service (a predecessor of part of the EPA), the U.S. Weather Bureau formed an air pollution unit under its Special Projects Section. It also detailed specialists to the Public Health Service to provide user-appropriate and scientifically credible air quality meteorological programs to support regulatory applications. Significant data collection and analysis efforts in the 1950s and 1960s led to a better understanding of air pollution episodes and the atmosphere’s controlling effect on air pollution (Heidorn 1978; Holzworth 1962). During this period, the Weather Bureau issued regional advisories of air pollution potential over the eastern United States (Niemeyer 1960; Boettger 1961) and municipal air quality agencies began to predict pollution on the local urban scale (e.g., Thuillier and Sandberg 1971).

In 1965, President Johnson formed the Environmental Sciences Services Administration (ESSA) from two longstanding Department of Commerce agencies: the Coast and Geodetic Survey (established by President Jefferson in 1807) and the Weather Bureau (established by Congress in 1891). In 1970, President Nixon combined ESSA with seven

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[2] In 1948 DOD established the Armed forces Special Weapons Project. This effort led to formation of the Defense Atomic Support Agency in 1959, which became the DNA in 1971.

other earth science programs to establish NOAA. By then, NOAA/ARL had five Divisions: Idaho Falls; Las Vegas; Oak Ridge; Washington, D.C.; and Research Triangle Park, North Carolina.[3] Also in 1970, President Nixon established the EPA. As part of the Clean Air Act Amendments of 1970 and 1977, the EPA focused on setting air quality standards and controlling pollution at its sources. The NOAA group assigned to support the EPA, now known as the Atmospheric Sciences Modeling Division (ASMD) of NOAA/ARL, serves as the primary vehicle through which EPA supports research efforts in air pollution meteorology and atmospheric modeling. ASMD conducts research activities in-house and through contract and cooperative agreements for the National Exposure Research Laboratory and other EPA groups. ASMD also provides technical information, observational and forecasting support, and consulting on all meteorological aspects of the air pollution control programs mandated by the Clean Air Act to the EPA offices of Air Quality Planning and Standards, Research and Development, and Air and Radiation. It also supports EPA regional offices and various State and local agencies.

During the 1970s and 1980s, air quality agencies prepared pollution predictions using objective statistical methods that required forecasts of atmospheric conditions as input (Aron and Aron 1978; Aron 1980; McCutchan and Schroeder 1973). In the 1980s, State Implementation Plans became a regulatory method to control air pollution at its sources by demonstrating how states would reduce emissions to meet the National Ambient Air Quality Standards. Numerical Eulerian grid models were used to develop State Implementation Plans by simulating historical air pollution episodes and demonstrating the effect of future emissions reductions. These models employed diagnostic wind field models to interpolate available meteorological observations to a three-dimensional grid (Collett and Oduyemi 1997). By the 1980s, the diagnostic models could be replaced with prognostic models (Chang et al. 1987). As prognostic real-time mesoscale meteorological models have matured, the air quality community has begun coupling them with air quality models, either keeping separate (offline) software for chemistry and meteorology (Vaughan et al. 2002; Hogrefe et al. 2001; Jakobs et al. 2001; McHenry et al. 2001) or using an integrated (online) approach (Grell et al. 2000).

Air chemistry models describe the fate and transport of atmospheric chemical constituents in both the gas and the aerosol phases. They now track about 100 chemical species, interacting through mechanisms involving hundreds of chemical reactions. Because of the important role that aerosols play in radiative transfer, weather, and health impacts, most air quality models now include detailed descriptions of aerosol dynamics and calculate size-resolved aerosol composition, radiances, and photolysis rates interactively with the cloud and aerosol fields. With today's computational power and efficiencies, air chemistry models can simulate pollution distributions in urban air sheds with spatial resolution of a few kilometers or they can cover the globe with horizontal grid spacing of less than 100 kilometers. These models are able to provide quantitative information on the distributions of many of the atmosphere's key trace gases and aerosols. Air chemistry models have become an essential element in atmospheric

[3] The ARL Cincinnati Office was moved to Research Triangle Park, North Carolina in 1969 specifically to provide support to the EPA.

chemistry studies. They also provide science-based input for decision makers locally, nationally, and globally.

Although meteorological and chemical processes are strongly coupled, until recently the chemical processes in air quality modeling systems were usually treated off line from the meteorological model, as in EPA's Community Multiscale Air Quality modeling system, whose output provided the transport function (Byun and Ching 1999). This type of system is usually termed a chemical transport model (CTM). In the newer online approach there is no CTM; the chemical processes are represented within the meteorological model. The online approach has a number of potential advantages for air quality forecasting, such as better characterization of the time-resolved dispersion of air pollutants.

Within the context of mesoscale meteorological modeling, the Weather Research and Forecasting (WRF) model is being developed cooperatively by many government laboratories and universities led primarily by the NOAA, the National Center for Atmospheric Research (NCAR), DOD, and the Federal Aviation Administration. The WRF model is well suited to become the cornerstone for a next-generation air quality prediction system.[4] This model, currently under development, is nonhydrostatic, with several dynamic cores as well as many choices for physical parameterizations to represent processes that cannot be resolved by the model. This flexibility allows the model to be applied on many scales. A first version of an online WRF-based air quality prediction system for ozone prediction already exists (http://box.mmm.ucar.edu/wrf/WG11); the chemical modules are based on the online MM5/chemistry model (Grell et al. 2000). The official future release of this model (planned for 2005) will include many additional chemical modules from other air quality prediction systems and a choice of offline coupling.

A.2 Field Studies

This section lists and summarizes ATD field studies that could prove useful for supporting future ATD research initiatives. The list is not exhaustive; it represents those studies that the JAG members considered to be of greatest potential value for ongoing R&D efforts, as discussed in chapters 5 and 6.

A.2.1 Point Source Dispersion Experiments

Dispersion of Near-Surface Releases

1. **Round Hill** was conducted in 1954/55 and 1957 using sulfur dioxide tracer (Cramer, Record, and Vaughan 1958). Ten-minute samples were measured for sulfur dioxide along three arcs (50, 100, and 200 m) downwind of a point source release. The release height for the 29 experiments in 1954/55 was 30 cm; the release height for the 10

[4] Background information on the WRF model and the latest applications and development news can be found on the Internet at http://wrf-model.org/.

experiments in 1957 was 50 cm. Receptor height was 2 m. Site roughness was greater than 10 cm. A unique feature of the 1957 experiments was that sampling was conducted for the first 0.5 min and 3-min of the 10-minute sampling periods.

2. **Project Prairie Grass** was conducted in 1956 with sulfur dioxide tracer (Barad 1958; Haugen 1959). It included 68 ten-minute samples taken at 1.5 m intervals along five arcs (50, 100, 200, 400, and 800 m) downwind from a point source release of sulfur dioxide 46 cm above ground. The 20-minute releases were conducted during July and August of 1956, with an equal number of cases run during the daytime and nighttime. Sampling was done during the 10-minute period in the middle of the 20-minute release. Site roughness was 0.6 to 0.9 cm.

3. **Green Glow** was conducted in 1959 with zinc sulfide tracer (Fuquay, Simpson, and Hinds 1964; Nickola 1977). Thirty-minute samples of zinc sulfide were taken along six arcs (200, 800, 1600, 3200, 12,800, and 25,600 m) downwind from a point source release 2.5 m above ground. Receptor height was 1.5 m. Site roughness was 3 cm.

4. **Hanford-30** was conducted in 1960–1961 with zinc sulfide (Fuquay, Simpson and Hinds 1964; Nickola 1977). Zinc sulfide samples were collected at 20 to 75 minutes along five arcs (200, 800, 1600, 3200, 12,800 m) downwind from a point source release 2.5 m above ground. Receptor height was 1.5 m. Site roughness was 3 cm.

5. **Dry Gulch** ws conducted in 1961–1962 with zinc sulfide (Haugen and Fuquay 1963). Thirty-minute samples of zinc sulfide were collected along five arcs (853, 1500, 2301, 4715, and 5665 m) downwind of a point source release 2 to 3 m above ground. Receptor height was 1.5 m. The terrain was sloping mesa cut by deep ravines; vegetation was mainly grasses with occasional brush and trees.

6. **Ocean Breeze** was conducted in 1961–1962 with zinc sulfide (Haugen and Fuquay 1963). Thirty-minute samples of zinc sulfide were collected along three arcs (1200, 2400 and 4800 m) downwind of a point source release 2 to 3 m above ground. Receptor height was 1.5 m. The terrain was rolling sand dunes covered with dense palmetto and brushwood.

7. **Hanford-67** was conducted in 1963–1973 with zinc sulfide, fluorescein, rhodamine B, and krypton-85 tracers (Nickola 1977). Ten-minute and 30-minute samples of zinc sulfide, fluorescein (uranine), rhodamine B, and krypton 85 were collected along eight arcs (from 200 to 12800 m) downwind of a point source release, mostly at 2 m with several at 1 m. Receptor height was 1.5 m. Site roughness was 3 cm. There were 23 experiments, most using dual tracers, including 14 with releases at both 2 and 26 m.

8. **Mountain Iron** was conducted in 1967 with zinc sulfide tracer (Hinds and Nickola 1967; Hinds 1968). Several 5 minute, but mostly 30 minute samples of zinc sulfide tracer were collected along arcs ranging from 260 m to 11.4 km from a 2 m point source release. The experiment site was rugged rolling terrain near the central California coast.

9. **Hanford-83** was conducted in 1983 with sulfur hexafluoride tracer (Doran and Horst 1985). Thirty-minute samples were collected for zinc sulfide and sulfur hexafluoride, which were jointly released from a point source 2 m above ground. Six experiments were run, with sampling at 1.5 m above ground and along five arcs ranging from 100 to 3200 m downwind. Site roughness was 3 cm. These experiments were conducted at the same site as the Green Glow, Hanford-30, and Hanford-67 experiments and had the objective of better characterizing the deposition properties of zinc sulfide.

10. **MADONA** was conducted in 1992 with sulfur hexafluoride and propylene gas tracers (Cionco et al. 1999). The multination Meteorology and Diffusion over Non-Uniform Areas (MADONA) field study was conducted at Porton Down, Salisbury, Wiltshire, United Kingdom. MADONA combined high-resolution meteorological data collection with diffusion experiments using smoke, sulfur hexafluoride, and propylene gas during unstable, neutral, and stable atmospheric conditions. The objective was to obtain terrain-influenced meteorological fields, dispersion, and concentration fluctuation measurements using specialized sensors and tracer generators. Thirty-one days of meteorological data were collected during the period September 7 through October 7, 1992. Twenty-seven diffusion experiments were conducted from September 14–23, 1992. Puffs and plumes of smoke and sulfur hexafluoride were released simultaneously for most of the experiments. This well-documented database is suitable for the evaluation and validation of short-range wind field and ATD models. The database was originally placed on CD-ROM in a structured way by the Chemical and Biological Defence Establishment, Porton Down. This database is now available from the Riso National Laboratory, Denmark, at <http://www/risoe.dk/vea-madona/ndescribtion.htm>.

Dispersion of Elevated Releases–Rural, Simple Terrain

1. **Hanford-67** was conducted in 1963-1973 with zinc sulfide, fluorescein, rhodamine B, and krypton-85 tracers (Nickola 1977). Ten-minute and 30-minute samples of zinc sulfide, fluorescein, rhodamine B, and krypton-85 were collected along eight arcs (from 200 to 12,800 m) downwind from a point source release. Receptor height was 1.5 m. Site roughness was 3 cm. There were 46 releases at 26 m and 20 releases at 56 m. There also were releases at 111 m, but no meteorological data are available for these cases.

2. **Cabauw** was conducted in 1977–1978 using sulfur hexafluoride tracer (Nieuwstadt and van Duuren 1979). In a series of 15 experiments, sulfur hexafluoride tracer was released at either 800 m or 200 m, with sampling at 1.5 m above ground along a single arc that ranged downwind from 3 to 5 km (depending on wind direction). Sampling was for two consecutive 30 minute periods. Site roughness varied from 10 to 20 cm, depending on wind direction.

3. **Kincaid** was conducted in 1980–1981 using sulfur hexafluoride tracer (Bowne et al. 1983). The sulfur hexafluoride tracer experiments conducted at Kincaid involved a release from a 183 m stack with a buoyant plume rise on the order of 200 m. There were 171 experiments conducted during April, May, and August of 1980 and May

and June of 1981. Measurements were made of near-surface hourly concentrations and hourly meteorology. There were twelve roughly defined receptor arcs ranging from 0.5 to 50 km from the release.

4. **Teruel** was conducted in 1985 with sulfur hexafluoride tracer (Sivertsen and Irwin 1987, 1996). Ten experiments were conducted in which sulfur hexafluoride was released from the 343 m stack of the 1200 MW Teruel coal-fired electric power plant. Two consecutive 15-minute samples were collected 1.5 m above ground along three arcs at approximately 10, 24, and 48 km from the stack. The plant is located 600 m above sea level on the southern side of the Ebro valley, midway between Madrid and Barcelona. Site roughness was estimated to be about 30 cm. A key objective of these experiments was to characterize the decrease in the transport speed (and thus the increase in the transport time) as the plume flowed toward the coast and into the strong sea breeze.

Dispersion of Elevated Releases–Rural, Complex Terrain

1. **Cinder Cone Butte** was conducted in 1980 using sulfur hexafluoride tracer (Snyder et al. 1985). During the autumn of 1980, 18 nighttime or early morning 8-hour tracer experiments were conducted at the 100-meter high hill at Cinder Cone Butte, which is near Boise, Idaho. The main tracer was sulfur hexafluoride; Freon 1381 was also used in ten experiments. Sampling was conducted with a network of approximately 100 samplers located on the slopes of the hill.

2. **Hogback Ridge** was conducted in 1982 using sulfur hexafluoride tracer and Freon 1381 (Snyder et al. 1985). In October 1982, 11 nighttime or early morning 8-hour tracer experiments were conducted along an approximately 1.5-km section of the 90 m high Hogback Ridge near Farmington, New Mexico. A network of 110 samplers located on the slopes of the ridge collected samples of sulfur hexafluoride and Freon 1381.

3. **Tracy Power Plant** was conducted in 1984 using sulfur hexafluoride tracer (Snyder et al. 1985). A feasibility study was conducted in November 1983, with a full-scale study in August 1984, at the Tracy Power Plant, which is located about 27 km east of Reno, Nevada. The site is located in the Truckee River Valley, with mountains surrounding the power plant on all sides. Peaks as high as 460 m above the stack base afforded opportunities for plume impaction in many directions. The power plant was maintained in warm standby condition as sulfur hexafluoride was injected in the base of the 91.4 m smokestack. The feasibility study consisted of 10 experiments during November 7–19, 1983, for a total of 90 hours of sampling at a network of 53 samplers. The full-scale study consisted of 14 experiments during August 8–27, 1984, for a total of 128 hours of data collection at a network of 110 samplers, mainly during late evening or early morning hours.

4. **ASCOT Studies**. Beginning with an exploratory field study in The Geysers geothermal region north of San Francisco, California, in 1979, the DOE funded a multi-year multi-organization study of ATD in complex terrain. The work included

both multiple tracers (sulfur hexafluoride, several perfluorocarbons, and other materials) and detailed micrometeorological measurements using both point and remote-sensing instruments. From 1979 to 1982, this work centered on valleys and basins astride the California coastal range. The emphasis then shifted for several years to a complex of simple individual valleys in the oil shale region north of Grand Junction, Colorado. Interest then shifted to the Front Range of the Rocky Mountains, near the DOE's Rocky Flats facility northwest of Denver. A field study was also performed in the ridge valley terrain of eastern Tennessee, which is typical of many areas near the Appalachian Mountains. Funding for ASCOT ended in the early 1990s.

5. **Model Validation Study.** Because of tightened limits on human exposures to the products of both normal and abnormal rocket launches at the Cape Canaveral Air Station and Vandenberg Air Force Base ranges, the Rocket Exhaust Effluent Dispersion Model, which was used to predict concentrations from launches, was leading to too many weather-induced launch delays. In hopes of reducing the number of expensive launch delays while still protecting public health, the Air Force funded a series of transport and diffusion studies at the two sites in 1995 and 1996. To simulate the elevated releases expected from a rocket, a blimp was used to release sulfur hexafluoride tracer. Near-ground releases were also used. An extensive network of time-integrating samplers and a small network of mobile fast-response samplers mounted in vans were used to measure ground-level concentrations. Fast-response analyzers were also mounted in two Global Positioning System (GPS)–equipped light airplanes to measure concentrations aloft. Both launch ranges have extensive meteorological systems in place. These were supplemented by point and remote-sensing instrument systems. Three 3-week seasonally spaced studies were performed at Cape Canaveral Air Station; one study was conducted at Vandenberg Air Force Base. Although the Cape Canaveral area is flat, the site is considered complex terrain because of the land–water contrasts and the wide range of land types. Vandenberg is in the midst of quite complex terrain. Both sites are subject to land–sea circulations.

Point Source Releases in Urban Terrain

1. **St. Louis** was conducted from 1963 to 1965 using sulfur dioxide tracer (McElroy and Pooler 1968). From the spring of 1963 to the spring of 1965, 26 daytime and 16 evening experiments were conducted involving 1-hour releases of zinc sulfide from two site locations (Forest Park and a rooftop release from the Knights of Columbus Building). Sampling (total dose) was conducted typically along three arcs that ranged from 1 to 7 km from the release site, with a few cases having an arc at 15 km. The initial lateral dispersion was estimated at 50 to 60 m (length of a typical city block, 160 m, divided by 4.3), with larger values when the wind was diagonally across the block. The initial vertical dispersion was estimated at 20 to 30 m. The authors concluded that dispersion from low-level sources in urban areas for downwind distances of less than 800 m is conjectural.

2. **Copenhagen** was conducted in 1978–1979 using sulfur hexafluoride tracer (Gryning and Lyck 1984, 2002). This series of ten tracer experiments in the Copenhagen area was carried out under neutral and unstable atmospheric conditions. The sulfur

hexafluoride tracer was released without buoyancy from a tower at a height of 115 m and sampled at 2–3 m above ground level on up to three crosswind arcs at 2–6 km from the point of release. Three consecutive 20-minute averaged tracer concentrations were measured, allowing for a total sampling time of 1 hour. The site was mainly residential, having a roughness length of 0.6 m. The meteorological measurements performed during the experiments included standard measurements at multiple heights on the tower of tracer release, as well as three-dimensional wind velocity fluctuations at the height of release.

3. **METREX**. During all of 1983, fluorocarbon tracer was released at several locations around the Washington, D.C., beltway as part of the Metropolitan Experiment (Draxler 1985). The scale of this experiment, which was larger in both space and time than most urban studies, was intended to test dispersion models over the long term. Some supplementary meteorological data were collected in addition to the usual information from the sites around and within the Washington, D.C., metropolitan area.

4. **Indianapolis** was conducted in 1985 using sulfur hexafluoride. (Murray and Bowne 1988). Sulfur hexafluoride was released from an 84 m stack with buoyant plume rise. There were 170 experiments conducted during September and October of 1985, with measurements of near-surface hourly concentrations and hourly meteorology. Measurements were taken along twelve roughly defined arcs ranging from 0.2 to 12 km from the release.

5. **Lillestrom** was conducted in the town of Lillestrom (near Oslo), Norway, in 1987 using sulfur hexafluoride tracer (Haugsbakk and Tonnesen 1989). The experiments took place in a flat residential area with buildings and trees ranging from 6 to 10 m in height. The surface roughness was about 0.5 m. Sulfur hexafluoride was released from a mast 36 m above the ground. Near-surface samples were collected along three arcs for two sequential 15-minute periods. The crosswind tracer concentration profiles were well determined for all trials, enabling a relatively accurate estimate of crosswind-integrated concentration. The temperature during the tracer experiments was low (approximately -20° C), and the ground was snow-covered.

6. **Kit Fox** was conducted during late August and early September 1995. A "billboard" (flat plate) obstacle array was set up in the desert at Frenchman Flats at the Nevada Test Site. Local roughness was enhanced with a much larger array of much smaller obstacles. Carbon dioxide was used as the somewhat dense gaseous tracer, and an array of instruments provided horizontal and vertical meteorological measurements. The test is well documented and would make a good addition to a national archive.

7. **URBAN/VTMX** was conducted in 2000 with sulfur hexafluoride tracer (documentation at <http://urban.llnl.gov/experiment.html> and <http://www.pnl.gov/vtmx/>). The URBAN 2000 experiment, which was conducted during October 2–25, 2000, consisted of six intensive observation periods with nighttime releases of sulfur hexafluoride in downtown Salt Lake City, Utah. During this same period, the Vertical Transport and Mixing (VTMX) meteorological field

measurement program took take place in the Salt Lake Valley. VTMX was designed to study the processes contributing to vertical transport and mixing of momentum, heat, and water vapor in the lowest few thousand feet of the atmosphere. The Salt Lake Valley was chosen as the study site because the surrounding mountains often contribute to the development of cold pools (i.e., conditions in which colder air is trapped in the valley while warmer air is found at higher elevations). Vertical transport and mixing processes in these conditions can be particularly difficult to describe. Flows over the mountains and out of the canyons, as well as winds generated by the temperature contrasts between the Great Salt Lake and the valley floor, may generate wind shear and atmospheric waves. These phenomena can in turn modify the vertical structure of the atmosphere.

8. The **Mock Urban Settings Test (MUST)** was conducted during September 10–27, 2001, at the Dugway Proving Ground in Utah using propylene as the tracer (Biltoft 2001; Biltoft, Yee, and Jones 2002). A mock building array was created by placing shipping containers in a 10 x 12 regular aligned grid. Each shipping container was 12.2 m wide, 2.42 m deep, and 2.54 m high. They were aligned with the long face perpendicular to the prevailing nighttime drainage winds and daytime upslope winds. The plan area density of the array was 13 percent and the height-to-width ratio was 0.2, the latter indicative of the isolated roughness flow regime. Tracer gas puffs or plumes were released from positions within or immediately upwind of the MUST array. Tracer dispersion through the array was measured using fast-response photoionization detectors. A 32 m tower and several 6 m towers within the MUST array provided vertical sampling, while four sampling lines of photoionization detectors provided lateral dispersion information. Sixty-eight usable trial events, consisting of 63 continuous releases and 5 sets of puff releases, were completed during MUST, providing 16 hours of continuous release data and 4.75 hours of puff data for analysis.

9. **BUBBLE** was conducted in 2002 using sulfur hexafluoride tracer (Gryning et al. 2003). Between June 15 and July 12, 2002, a series of four experiments were conducted in Basel, Switzerland. Sulfur hexafluoride was released approximately 1.5 m above the rooftops with rooftop sampling at 12 locations distributed close to the release and extending out to about 1.6 km. The mean building height in the area was 15.1 meters, and the mean plan area density was 48 percent. Each experiment provided six 30-minute samples, starting at approximately 1400 LST. The aim was to perform the tracer experiments under Clara Wind conditions, a thermally-driven wind system that develops over Basel in the afternoon on cloud-free summer days and is characterized by persistent winds from the northwest.

10. The **Joint Urban 2003** Field Experiment was conducted in Oklahoma City, Oklahoma, during July 2003 (Halvorson et. al. 2004; <http://ju2003.pnl.gov/study.html>). Its focus was characterizing the flow of sulfur hexafluoride tracer gas in an urban environment. More than 150 government, university, and private sector participants supported high-resolution atmospheric measurements and other instrumentation during the experiment. The field program consisted of six daytime and four nighttime intensive observation periods, each lasting approximately eight

hours and typically including four puff releases and three 30-minute releases. The Joint Urban 2003 database (approximately 3 terabytes) is maintained by Dugway Proving Ground.

A.2.2 Possible Urban Testbeds

1. NOAA/ARL implemented a dispersion measurement testbed, **DCNet**, in the Washington, D.C., area to provide the best possible basis for dispersion computations needed for both planning and possible response.

2. The Brookhaven National Laboratory's Environmental Measurements Laboratory initiated the **Urban Atmospheric Observatory** in 2003 to establish a dense array of meteorological instrumentation, remote-sensing and satellite products, and model output, as well as radiation detection (gamma spectrometer) and aerosol measurements in a small area in the heart of downtown Manhattan in New York City.

A.2.3 Long Range Transport Studies

1. The **Atlantic Coast Unique Regional Atmospheric Tracer Experiment (ACURATE-82/83)**, which was conducted in 1982 and 1983, consisted of measuring the krypton-85 air concentrations from emissions of the Savannah River Plant in South Carolina (Heffter, Schubert, and Meade 1984). For 19 months from March 9, 1982, to September 30, 1983, 12- and 24-hour average air concentrations were collected at five locations along the United States east coast at distances of 300 to 1000 km from the plant (Fayetteville, North Carolina, to Murray Hill, New Jersey). Measurements were made of hourly krypton-85 emissions from the plant (in curies) and of air concentrations (in picocuries per cubic meter). Ambient background concentration at each measurement station was subtracted from measured concentrations. Background varied by latitude, increasing to the north due to the prevalence of nuclear fuel reprocessing in the northern latitudes.

2. The **Across North America Tracer Experiment of 1987 (ANATEX-87)** consisted of 66 perfluorocarbon tracer releases (33 each from two different locations) every 2.5 days from January 5 to March 26, 1987 (Draxler and Heffter 1989). Air samples were collected for 24-hour periods continuing over 3 months (January 5 to March 29) at 75 sites covering most of the eastern United States and southeastern Canada. Perfluorotrimethylcyclohexane was released from the site at Glasgow, Montana. Perfluorodimethylcyclohexane and perfluoromonomethylcyclohexane were released from the site at St. Cloud, Minnesota. Release units are recorded in grams; air concentrations were recorded in picograms per cubic meter. The two tracers released from the St. Cloud site were released at the same time and therefore do not provide any meteorologically independent data.

3. The **Cross Appalachian Tracer Experiment (CAPTEX-83)** was conducted during September and October of 1983 (Ferber et al. 1986). It consisted of six 3-hour releases of perfluorocarbon tracer, four from Dayton, Ohio, and two from Sudbury, Ontario, Canada. Samples were collected at 84 sites 300 to 800 km from the source as

3- and 6-hour averages for about 48 hours after each release. One additional short (30 minutes) tracer release from Dayton was not evident in the sampling data.

4. The **Idaho National Engineering Laboratory releases in 1974 (INEL74)** consisted of about two months of krypton-85 releases, from February 27 to May 5, 1974, with continuous 12-hour sampling from February 27 to May 4, 1974, at 11 locations in a line about 1500 km downwind (Oklahoma City, Oklahoma, to Minneapolis, Minnesota). The same ambient background concentration (13.7 pCi/m^3) was subtracted from all stations (Ferber et al. 1977, Draxler 1982).

5. The **Oklahoma City 1980 experiment (OKC80)** was a single release of two different perfluorocarbon tracers on July 8, 1980, over a 3-hour period (Ferber et al. 1981). From July 8 to July 11, 1980, 3-hour samples were collected at 10 sites 100 km downwind and at 35 sites 600 km downwind from the Oklahoma City release point.

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APPENDIX B. FEDERAL CAPABILITIES AND RESEARCH AND DEVELOPMENT PROGRAMS

The dispersion modeling and consequence assessment capabilities of Federal departments and agencies are described below. Programs and activities of the Departments of Commerce, Defense, Energy, and Homeland Security are covered, as are programs in the National Aeronautics and Space Administration (NASA) and the U.S. Environmental Protection Agency (EPA). The information on programs presented here was current as of September 2004. Program details are subject to change.

B.1 U.S. Department of Commerce, National Oceanic and Atmospheric Administration

Within the context of atmospheric dispersion modeling, the National Oceanic and Atmospheric Administration (NOAA) is the principal supporting agency for atmospheric forecasts. NOAA provides meteorological and other products tailored for response applications. In partnership with the EPA, NOAA provides the dominant first-responders' dispersion model capability, the CAMEO/ALOHA modeling system, which is now in use by 10,000 to 20,000 emergency responders nationwide. NOAA provides dispersion forecasts based on the Nation's operational domestic mesoscale weather data and prediction models, both routinely (four times daily for selected sites) and on an around-the-clock on-demand basis. Through its 122 Weather Forecast Offices, NOAA provides weather and dispersion forecasts nationwide. Through its Realtime Environmental Applications and Display System (READY), it provides the dispersion forecasting capability that is a central element of the emergency systems of a large number of States and other emergency response organizations.

NOAA provides forecasts of dispersion for international applications through its role as one of seven international sources recognized by the World Meteorological Organization. The other Regional Specialized Meteorology Centers for dispersion are located in Canada, Australia, Russia, England, France, and China. The NOAA modeling system is used by Australia and China.

NOAA is a principal sponsor of the Weather Research and Forecasting (WRF) model. The WRF model is being developed as a collaborative effort among the Mesoscale and Microscale Meteorology Division of the National Center for Atmospheric Research (NCAR), the Environmental Modeling Center of the NOAA National Centers for Environmental Prediction (NCEP), the Forecast Research Division of the NOAA Forecast Systems Laboratory, the Air Force Weather Agency (AFWA) in the Department of Defense (DOD), the Federal Aviation Administration, the Center for the Analysis and Prediction of Storms at the University of Oklahoma, and other university-based scientists.

B.2 U.S. Department of Defense

B.2.1 U.S. Northern Command

The mission of the DOD is to provide the military forces needed to deter war and to protect the security of the United States. Within the DOD, the U.S. Northern Command (NORTHCOM) is the lead activity for homeland defense.

NORTHCOM plans, organizes, and executes homeland defense and civil support missions. Specifically, it will conduct operations to deter, prevent, and defeat threats and aggression aimed at the United States, its territories, and interests within its assigned area of responsibility. As directed by the President or Secretary of Defense, NORTHCOM provides military assistance to civil authorities, including consequence management operations.

Under NORTHCOM is the Joint Task Force for Civil Support (JTF-CS). The mission of JTF-CS is to provide command and control for DOD forces deployed in support of the Department of Homeland Security, Federal Emergency Management Agency (DHS/FEMA) to save lives, prevent injury, and provide temporary critical life support. DHS/FEMA is responsible for managing the consequences of a chemical, biological, radiological, nuclear or high-yield explosive (CBRNE) incident in the United States or its territories and possessions. As part of DOD's overall effort in support of the Terrorism Incident Annex added to the Federal Response Plan in 1997, JTF-CS is prepared to respond to requests for assistance from the lead Federal agency (LFA) following a CBRNE incident. When approved by the Secretary of Defense, JTF-CS supports the LFA in charge of consequence management—most likely DHS/FEMA.

B.2.2. Defense Threat Reduction Agency

The Defense Threat Reduction Agency (DTRA) safeguards America's interests from CBRNE used as weapons of mass destruction (WMD) by controlling and reducing the threat and providing quality tools and reach-back services for the warfighter and first responders in the event of a terrorist attack or hazardous material release. In an incident, DTRA will be asked by the LFA to participate in all National Special Security Events.

DTRA Operational and Analytical Support

DTRA provides operational and analytical support to the DOD and other organizations for critical WMD defense and response to related catastrophic events. Dispersion modeling and consequence assessment capabilities are an important element of this support. DTRA provides scientific and physics-based software tools that are easily deployed on a laptop personal computer. As part of its suite of consequence analysis tools, DTRA supports the user with on-demand meteorological data servers that provide real-time and forecasted four-dimensional weather, terrain, and land-use data from NOAA, U.S. Air Force and Navy, DTRA, Air Force Combat Climatology Center, and NCAR. DTRA supplies the research and development, training, and technical support needed for automated software systems to accurately predict the effects of hazardous material releases into the atmosphere and their impact on civilian and military populations. The agency also supports emergency response for matters involving WMD events through the use of deployable Consequence Management Advisory Teams (CMATs), a 24-hour, 7-day-per week (24/7) continuous operations center, and technical reach-back support. Technical reach-back support, through the 24/7 Operations Center, provides DTRA assistance to user's with immediate CBRNE response and consequence management needs. DTRA's active development program is bringing new software tools to the user, providing decision support information consistent with operational concepts integrated vertically across all echelons in a Common Operating Picture environment. All these tools are available in a web-based, collaborative, net-meeting-type, geographical information system (GIS) environment for the use of operators, warfighters, and first responders. DTRA has a proven record of transitioning research and development software tools for operational use.

DTRA Research and Development Programs By Topic Area

Hazard Prediction and Assessment. DTRA's Hazard Prediction and Assessment Capability (HPAC) program relies on various types of weather products to support transport and diffusion calculations and corresponding hazard predictions. Currently, DTRA provides three types of weather analyses in real time to its HPAC users: historical weather, observations, and forecasts. In addition to providing the HPAC user community with 24/7 operational meteorological data, the DTRA meteorology program is engaged in basic and applied atmospheric R&D to further improve its hazard assessment tools.

Numeric Weather Prediction (NWP). DTRA provides NWP data to its customers from various models with grid resolutions from as coarse as 80 km to as fine as 1 km. For applications such as collateral effects from large nuclear strikes, coarse global-scale data suffice to characterize the fallout pattern over regional areas. At the other extreme, a chemical attack on a city or in a populated open area requires knowledge of the wind flow at resolutions corresponding to the local terrain: typically on the order of a few kilometers. Therefore, DTRA conducts basic research to improve NWP capabilities in general with particular emphasis on advances that can improve high-resolution modeling.

Current research efforts funded by DTRA include expanding the capacity of mesoscale models to incorporate remotely sensed datasets such as radar and satellite-derived wind fields, the creation of high-resolution local analyses, and the potential use of emerging urban observational networks. Other projects are focused on improving land use parameterizations to provide better specifications of the urban canopy. Since DTRA makes use of data from numerous NWP modeling systems, research also is being conducted to determine biases associated with these systems and the appropriate measures of NWP forecast accuracy of these models at differing model resolutions.

Weather Uncertainty. Meteorological predictions are inherently uncertain due to the stochastic nature of the atmosphere. Therefore, forecasts of meteorological quantities are incomplete if not accompanied by estimates of forecast precision. An accurate characterization of NWP forecast uncertainty is imperative when applied to atmospheric transport, dispersion, and associated downwind hazard assessment. Due to the probabilistic framework of the HPAC toolset, DTRA is particularly interested in capturing the variability in predicted values of meteorological variables for inclusion in transport and diffusion calculations.

Current research efforts designed at improving uncertainty estimates are focused primarily on the application of ensemble methodologies. In particular, DTRA-sponsored studies are currently investigating such issues as the minimum number of ensemble members needed to construct a statistically significant ensemble, real-time ensembling of DTRA's operational NWP data sets, ensemble generation at the mesoscale, and the validation of ensemble members through real-time model performance statistics. Also, DTRA is sponsoring a university study directed toward improving the existing empirical uncertainty model within HPAC.

Data Manipulation and Dissemination. Several developmental efforts to improve the dissemination of data to DTRA customers are ongoing, including the development of new architecture and software for the Meteorological Data Servers system. Once complete, these systems will provide state-of-the-art ingest, data manipulation, and server capabilities for DTRA's user community. DTRA is also actively involved in the development of advanced methods to reduce meteorological data transfer times. This research is directed toward intelligent methods of "thinning" large high-resolution NWP data sets to reduce overall size and improve delivery to end users.

B.2.3 U.S. Army

The Army has the responsibility to provide fundamental knowledge of the atmospheric boundary layer (ABL) over land to all U.S. armed services. Army programs concerned with ATD include the Atmospheric Sciences R&D program within the Army Research Laboratory, the Chemical Stockpile Emergency Preparedness Program (CSEPP), and the Army Research, Development, Test, and Evaluation (RDT&E) Meteorology Program.

Atmospheric Sciences R&D program. This program within the Army Research Laboratory is located at the Army Research Office (Research Triangle Park, North Carolina) and the Battlefield Environment Division (Adelphi, Maryland, and White Sands Missile Range, New Mexico). The program is broadly based to address the wide spectrum of physical conditions of the ABL and its influences on Army operations and systems. The program is divided into three general research areas: Atmospheric Sensing, Atmospheric Modeling, and Atmospheric Effects.

- *Atmospheric Sensing.* ATD-related concerns in this area include rapid detection, identification, and quantification of chemical and biological agents, both gases and aerosols, and in situ characterization and volumetric remote sensing of the state of the environment.
- *Atmospheric Modeling.* Within this area, the ARL focuses on understanding and modeling the diurnal dynamics of the ABL and on assimilation and fusion of volumetric measurement of atmospheric state variables at high resolution in

complex and urban domains. The effort results in the fusion of data with appropriate models to provide a real-time picture of the present state of the ABL and its likely development over short time periods, especially as they apply to ATD nowcasting. While working to reduce the uncertainty in data-fused model results, the Army Research Laboratory recognizes the need to communicate that uncertainty together with best estimates of expected ATD conditions in user-friendly products to decision makers at all echelons.

- *Atmospheric Effects.* End users of ATD modeling systems are often most interested in quantifying the effects of the atmosphere and assessing its impacts on their systems, operations, and personnel. ATD-related concerns are to provide those parameters at the spatial and temporal scales needed to determine relevant effects such as visibility effects of aerosols and dosage effects on personnel. The research results are incorporated into the weather modeling and support functions of the integrated meteorological system deployed to support training and field operations.

Chemical Stockpile Emergency Preparedness Program. The U.S. Army serves as DOD Executive Agent for the chemical weapons stockpile. Chemical weapons are stockpiled at eight locations: Aberdeen, Maryland; Lexington, Kentucky; Anniston, Alabama; Newport, Indiana; Pine Bluff, Arkansas; Pueblo, Colorado; Tooele, Utah; and Umatilla, Oregon. As a signatory to several international treaties, the United States has agreed to destroy its stockpile of chemical weapons. The Congress mandated in Public Law 99-145 that the Army provide *maximum protection* to the workers, general population, and the environment during the storage and destruction of these chemical weapons.

CSEPP focuses on the protection of the general population in the unlikely event of an accident involving the chemical stockpile. At the national level, the program is jointly managed by the U.S. Army Chemical Materials Agency and FEMA. The Program Office is at Aberdeen Proving Ground, Maryland. CSEPP provides funding and technical assistance to ten states and 41 counties in the vicinity of the chemical stockpile. (Newport is located approximately six miles from the Illinois border and Umatilla is located approximately three miles from the Washington border).

The D2-Puff model serves as the primary chemical hazard prediction tool in support of the US Army stockpile and non-stockpile programs. (The non-stockpile program handles demilitarization of chemical weapons or agents not included in the stockpile as defined by treaty and law, such as items uncovered from old ordnance disposal sites.) This segmented plume model is used daily in the planning for and potential response to accidents involving the chemical weapons stockpile. The primary stockpile chemical agents include the nerve agents sarin (designated GB in Army applications) and VX and the blister agent mustard (designated H in Army applications). The primary non-stockpile chemical agents include mustard, phosgene, and lewisite. The primary accidents of concern include spills, explosions, fires, and stack releases.

The D2-Puff model incorporates several sources of real-time meteorological data, both on-post and off-post. Meteorological towers have been built specifically to support the modeling system on the depots as well as in several nearby communities. In addition, the modeling system captures data from nearby NOAA National Weather Service (NWS) and university sites, as well as NOAA/NWS forecasts available via the Internet. With these data, the model continually generates wind fields and hypothetical chemical plume projections to support ongoing chemical weapons storage and demilitarization operations. The model typically updates every 15 minutes to account for temporal and spatial variability in the wind field due to the surrounding complex terrain.

The modeling system connects Army depot operations centers with State and county emergency managers to allow rapid transmission of emergency management information. This information includes an automated communication system, a GIS, a model to support shelter-in-place strategies, and report summaries.

The Army RDT&E Meteorology Program. The Army RDT&E Meteorology Program at Dugway Proving Ground, Utah, is responsible for providing operational meteorological support to U.S. Army RDT&E activities. The program is a user of ATD models, not a developer. However, as the principal DOD test center for chemical and biological defense systems, Dugway Proving Ground has a long history of ATD model R&D. It continues to provide technical assistance to other DOD agencies in ATD model R&D, including conducting field dispersion tests or experiments. Operational meteorological support of field tests involving releases of simulants of chemical and biological agents also requires that Dugway Proving Ground use ATD models in essentially the same ways that they are or could be used for homeland security applications.

The Army RDT&E Program also sponsors applied R&D on mesoscale meteorological modeling. These efforts benefit ATD modeling because the accuracy of the gridded mesoscale model output used as inputs to ATD models is at least as important to the validity of CBRNE hazard assessments as the accuracy of the ATD models themselves.

B.2.4 U.S. Air Force

Air Force Weather resources are organized into a three-tiered structure to conduct worldwide operations and support homeland defense. The Air Force Weather Agency (AFWA) is the strategic-level center. It provides meteorological satellite processing, weather models (mesoscale NWP, cloud analysis/forecast, snow depth, surface temperature, and land-surface models), strategic-level weather products, and specialized support to Special Operations Forces and the intelligence community. The second tier consists of the Operational Weather Squadrons (OWSs), each of which supports a specific geographic area of responsibility. Each OWS provides forecasts, warnings, and advisories to a large number of Air Force and Army active duty, Reserve, and National Guard locations, which support numerous U.S. sites. The level of support is second only to NOAA/NWS. The OWSs provide homeland security support to NORTHCOM when tasked. The third tier consists of Combat Weather Teams, which provide mission-tailored support to local base and tactical units of the Air Force, Army, Special Operations Forces, and other specialized military units. The Combat Weather Teams also provide the observations from their locations, which are disseminated to AFWA and, in most cases, also to the World Meteorological Organization for worldwide use.

B.2.5 U.S. Navy

The Navy's capability to provide operational support for homeland security is based on its expertise in conducting a Rapid Environmental Assessment and providing real-time environmental support, based on that assessment, for naval forces. The Navy's strengths in characterizing the environment through observations and modeling, together with its distributed facilities and effective network for communications and data exchange, are substantial contributions to the national requirement for the best meteorological and oceanographic support to the mission of homeland security. The Navy operates two primary Meteorology and Oceanography (METOC) production (modeling) centers, three regional METOC centers, and numerous facilities and detachments throughout the United States that work closely with NOAA operation centers. The Navy’s METOC community also owns seven military survey ships equipped with the latest oceanographic digital data collection systems to survey critical areas worldwide.

B.3 U.S. Department of Energy

B.3.1 Nuclear Incident Response Teams

The Department of Energy (DOE) and the DHS are jointly responsible for the Nuclear Incident Response Team (NIRT) assets that would be used in response to a domestic nuclear release incident. A February 28, 2003, memorandum of agreement (MOA) between the two departments established a framework for DHS to use various DOE assets. The MOA delineates functions and responsibilities for the control, utilization, and exercise of, and the standards for, NIRT assets. NIRT assets, with the exception of the Radiological Assistance Program, which may continue to self-deploy under circumstances where self-deployment is currently authorized, will deploy at the direction of DHS for domestic events in connection with an actual or threatened terrorist attack, major disaster, or other emergency in the United States. NIRT assets include the:

- Accident Response Group;
- RAP;
- Aerial Measuring System (AMS);
- National Atmospheric Release Advisory Center (NARAC);
- Federal Radiological Monitoring and Assessment Center (FRMAC);
- Radiation Emergency Assistance Center/Training Site; and
- Nuclear Emergency Support Team.

B.3.2 National Atmospheric Release Advisory Center

NARAC, which is located at Lawrence Livermore National Laboratory (LLNL), provides atmospheric plume modeling tools and services for chemical, biological, radiological, and nuclear (CBRN) airborne hazards—both gases and particles. These capabilities employ real-time access to worldwide meteorological observations and forecasts via redundant communications links to resources of NOAA, the U.S. Navy, and the U.S. Air Force. NARAC can simulate downwind effects from a variety of scenarios, including fires, radiation dispersal device explosions, hazardous material (HAZMAT) spills, sprayers, nuclear power plant accidents, and nuclear detonations. A database of potential sources is maintained for input to NARAC models. The NARAC software tools include stand-alone local plume modeling tools for end user's computers, and Internet web-based software to provide reach-back access to advanced modeling tools and expert analysis from the national center at LLNL. Initial automated, advanced three-dimensional predictions of plume exposure limits and protective action guidelines for emergency responders and managers are available in 5 to10 minutes. On-duty or on-call NARAC staff can follow up these initial products with more detailed analyses developed immediately, 24/7. NARAC continues to refine calculations using on-scene information, including measurements, until all airborne releases have stopped and the hazardous threats are mapped and the impacts are assessed. Model predictions include the three-dimensional and time-varying effects of weather, land use, and terrain. NARAC provides a simple GIS for display of plume predictions with affected population counts and detailed maps. It can also export plume predictions to other standard GIS systems.

NARAC supports the NIRT, the regional RAP teams, AMS, FRMAC, the DHS under the DOE–DHS MOA, and 40 DOE and DOD online sites. NARAC's operational support to 5 cities and 53 State and Federal organizations across the country has been successfully demonstrated under DHS and DOE oversight.

B.4 U.S. Department of Homeland Security

The capabilities of the DHS Emergency Preparedness and Response (DHS/EP&R) Directorate include an agency-wide GIS Service Center, which has evolved since 1994 from the Mapping Analysis Center (MAC). The MAC had originally supported the FEMA Emergency Support Team and the Response and Recovery Directorate. At the GIS Service Center, the results of the various modeling software packages are incorporated with remote-sensing data and imported into multiplatform GIS software for subsequent analysis. Experts in the scientific and modeling community determine the parameters used to operate these highly complex and complicated programs. DHS/EP&R maintains Internet and Government intranet sites, as well as a continuity of operations site with a capability almost identical to the GIS Service Center. DHS/EP&R is in the process of installing secure classified communications.

B.5 National Aeronautics and Space Administration

As an R&D agency, NASA has invested in three areas applicable to ATD: sensor technology, platform technology, and modeling and computing.

Tropospheric chemistry is considered to be the next frontier of atmospheric chemistry, and understanding and predicting the global influence of natural and human-induced effects on tropospheric chemistry will be the next challenge for atmospheric research over the foreseeable future. NASA's interest in trace gas species in the troposphere has driven investment in a number of active sensing techniques, e.g., differential absorption lidar. Experimental airborne prototypes are being developed and tested in various suborbital missions for tropospheric profiling of chemical species and may be adapted or used in homeland security applications.

NASA is also investing in autonomous suborbital platforms that simultaneously enable in situ planetary exploration and improve the targeting capability of Earth observational systems. Investments in airspace improvements that provide unmanned aerial vehicles (UAVs) with access to the National Airspace System and with in-vehicle technology for safe robotic flight in populated areas can directly enable in situ observations of hazardous airborne material without endangering pilots.

For many years, NASA has invested significantly in the development of data assimilation systems (DASs), especially global systems for medium-range weather forecasting and for climate, and in the study and understanding of forecast and modeling uncertainties. This data assimilation work now extends to the development of land-surface DASs and their integration into atmospheric simulation systems, to the development of an ocean DAS, and to collaboration with the National Weather Service to build a mesoscale atmospheric DAS. NASA's data assimilation work is also being applied to the study of the Earth's carbon cycle and to the study of global precipitation and of the Earth's hydrologic cycle.

While much of NASA's work with data assimilation and with forecast and modeling uncertainty has been applied to spatial and temporal scales much larger than those relevant to ATD modeling, a great deal of the technology that has been developed and many of the lessons that have been learned can be transferred directly to smaller scales. The real challenge is to build a program where people from a varied range of disciplines can talk to each other.

NASA has had extensive experience in using observation system experiments (OSEs) to evaluate the impact of various observations on global-scale atmospheric predictions and in using observation system simulation experiments (OSSEs) that first simulate the atmospheric observations and then predict the impact that these simulated observations would have on atmospheric predictions. These same OSE and OSSE techniques can be used to determine the impact that on-site data will have on ATD simulations and thereby help build ATD sensor networks.

NASA has invested heavily in multi-model ensemble techniques to better understand model and observation uncertainty. Ensemble Kalman filters have been used to estimate model spread and to thereby significantly reduce the number of ensemble members necessary, compared with those needed in a straightforward Monte Carlo approach. The agency has also carried out research on the use of the breeding vector to generate optimal forecast ensembles. All of these ensemble techniques can be fully adapted to the art of data assimilation for ATD modeling.

B.6 U.S. Environmental Protection Agency

As explained in appendix A, section A.1.2, the Atmospheric Sciences Modeling Division (ASMD), Air Resources Laboratory (ARL), NOAA, serves as the primary vehicle by which EPA funds its research efforts in air pollution meteorology and atmospheric modeling. ASMD conducts research activities in-house and through contract and cooperative agreements for the National Exposure Research Laboratory and other EPA groups. ASMD also provides technical information, observational and forecasting support, and consulting on all meteorological aspects of the air pollution control program to many EPA offices, especially the Office of Air Quality Planning and Standards. ASMD has identified five major research themes, summarized below, to guide its future research program development and resource planning efforts.

B.6.1 New Directions to Criteria Pollutants and Air Toxics Modeling

This research theme addresses the original and still primary area of research for which ASMD was created. The main research product is state-of-the-science modeling tools for assessment and mitigation of criteria pollutants and air toxics. Following the “one atmosphere” concept, the main tool for computer simulation of a multitude of air quality issues is currently the Community Model for Air Quality (CMAQ) system. While the CMAQ is adaptable to various meteorological models, ASMD has used only the Pennsylvania State University–NCAR Mesoscale Model (MM5). Future efforts will involve a gradual transition to the WRF model, which will be the next-generation mesoscale model for both research (replacing MM5) and operational forecasting (replacing the Eta and Rapid Update Cycle models). ASMD is becoming increasingly involved, especially in the chemistry component. WRF-Chem will be an "on-line" meteorology-chemistry model, representing a major step forward in the state of the science.

Current research includes upgrades to the meteorology–chemistry interface program, upgrade linkages to the WRF model, initial testing of WRF-Chem, and installing the PX-land surface planetary boundary layer (PBL) model into WRF-Chem. Upgrades are being made to the emissions processors to include wildfire, fugitive dust, and sea salt emissions. New gas-phase chemical mechanisms, readers, and solvers are being installed into CMAQ and tested. Research is being conducted to improve the condensed chemistry for long-term simulations. Updates are being made to the cloud dynamic processes and aqueous chemistry. A new version of CMAQ is scheduled for release in June 2004.

Improvements are being made to the CMAQ photolysis rates and radiative transfer model, including the addition of feedbacks between aerosols and radiation. A sectional model for treatment of aerosols is being added to CMAQ. The CMAQ plume-in-grid model is being extended to include aerosol chemistry. The CMAQ code is being optimized to reduce execution speed with testing on various platforms and compilers. Research is underway to include simulation of mercury chemistry and fate in CMAQ.

The plume dispersion model AERMOD is being updated to include dry and wet deposition. Fluid and wind tunnel simulations are being conducted to investigate sub-grid-scale phenomena, dispersion within convective boundary layers, and urban canyons. Computational fluid dynamics (CFD) modeling is being conducted in support of wind tunnel simulations of flow and dispersion around the World Trade Center site as part of the post-September 11, 2001, risk assessment for the New York City area. Research is being conducted to characterize sub-grid concentration distributions, including large eddy simulation with air chemistry and the probability distribution function of emissions.

B.6.2 Air Quality and Global Climate Change

From the air quality perspective, global climate change may make it more difficult in the future for the United States to achieve its air quality standards or goals at the regional and local level. Conversely, air pollution emanating from the United States, including methane, carbon dioxide, particles, and other constituents, may be exacerbating the rate of climate change. Climate change impacts act on long time scales (decades to centuries) and thus are difficult to detect. ASMD has established three research areas that address simulations of global air quality and the attendant effects of climate change: (1) assessment of intercontinental transport, (2) assessment of global climate change on regional/urban air quality, and (3) assessment of regional air quality on global climate change.

One current research activity involves MM5 regional climate modeling simulations based on downscaled global climate model results for current and future years. Another activity is investigating emissions processing for current and future climate change conditions.

B.6.3 Air Quality Forecasting

A national real-time air quality forecast model will equip State and local air quality agencies with a tool for making accurate, multi-day predictions of air quality. The public can use these forecasts to reduce individual exposure to harmful levels of ozone and particulate matter during elevated pollutant episodes. The real-time modeling results can also be used for aiding decision makers in issuing air pollution advisories, for regulating controlled burns, and for helping the public to visualize air quality patterns. The goal of this emerging research program is to design, develop, and test models for real-time forecasting of airborne material. The goal of this research is to construct an operational national air quality forecasting system for ozone and particulate matter. This research theme supports EPA's mission "to protect public health and welfare" and NOAA's mission "to forecast changes in atmospheric conditions."

Current research under this theme includes: (1) evaluation of summer ozone and fine particle simulation results for 2002 and 2003 for the northeastern United States, (2) collaboration and assistance to NOAA/NCEP in installing improvements and efficiencies in the operational modeling system for air quality forecasts, and (3) improved aerosol and radiation process treatment in the WRF-Chem air quality model to allow for meteorological and chemical feedbacks.

B.6.4 Multimedia Modeling

Many of the most difficult challenges facing the EPA span environmental media. Specific multimedia issues of concern include mercury, pesticides, hazardous waste, and excess nutrients. Effectively addressing these issues requires an improved understanding of cross-media processes. This research area will address the interaction of the atmosphere with adjoining media critical to nitrogen/nutrient cycling, acid deposition, and ozone formation and destruction, as well as the behavior of mercury and other toxic pollutants in the environment. Research activities include development of a multimedia nitrogen deposition model.

B.6.5 Data Management and Analysis Research

Many of the environmental issues currently being addressed will require simulations that demand significantly more computational resources and more complex model configurations than present activities require. As the scope of models increases and the models become more sophisticated, the amount of data they consume and generate will also increase. One area of ongoing research is to develop and test methods to address these data management issues.

A second area of ongoing research is to develop and test methods for data analysis and visualization. The growing volumes of data collected and generated will increasingly strain our ability to analyze the data. Much data analysis still relies on a human being looking at the data or at summaries of the data. This approach will become increasingly impractical as data volumes increase.

The ability of our modeling systems to replicate meteorological and chemical processes can only be determined through rigorous model evaluation. A third area of research is to develop and test improved methods for summarizing and characterizing model performance.

Research being conducted within this theme includes development and testing of model evaluation metrics that assess the ability of regional-scale modeling of ozone and aerosols to replicate seasonal spatial and temporal trends. A comparison is planned to assess the performance of several regional-scale mercury models. Quality assurance analysis tools are being developed for assessment of MM5 meteorology and the emissions processed for use in CMAQ.

APPENDIX C. ATMOSPHERIC TRANSPORT AND DIFFUSION MODELING CONSIDERATIONS

C.1 Hierarchy Theory

Most environmental models implicitly employ hierarchy theory in their construct, which in turn employs the concept of scale. Hierarchy theory is an extension of systems theory that attempts to analyze the effects of scale on the organization of complex systems. Simon (1973) was one of the first to argue for hierarchical systems in which each level communicates a small set of information or quantity of material to the next heigher (slower and coarser) level, and each level is formed from the interactions among a set of variables that share similar speeds (and geometries). O'Neill (1988) expanded this idea by shifting attention from the small-scale view to a multiscale view that recognized that processes could develop mutually re-enforcing relationships. Hierarchy theory has been used to separate the large and slow processes from the small and fast processes. Many have argued that environmental phenomena tend to have characteristic spatial and temporal scales (Simon and Ando 1961; Delcourt, Delcourt, and Webb 1983; Urban, O'Neill, and Shugart 1987). This hypothesis is supported empirically by the fact that many physical and ecological phenomena arrange themselves approximately along the 45^{o} line as depicted in figure C-1.

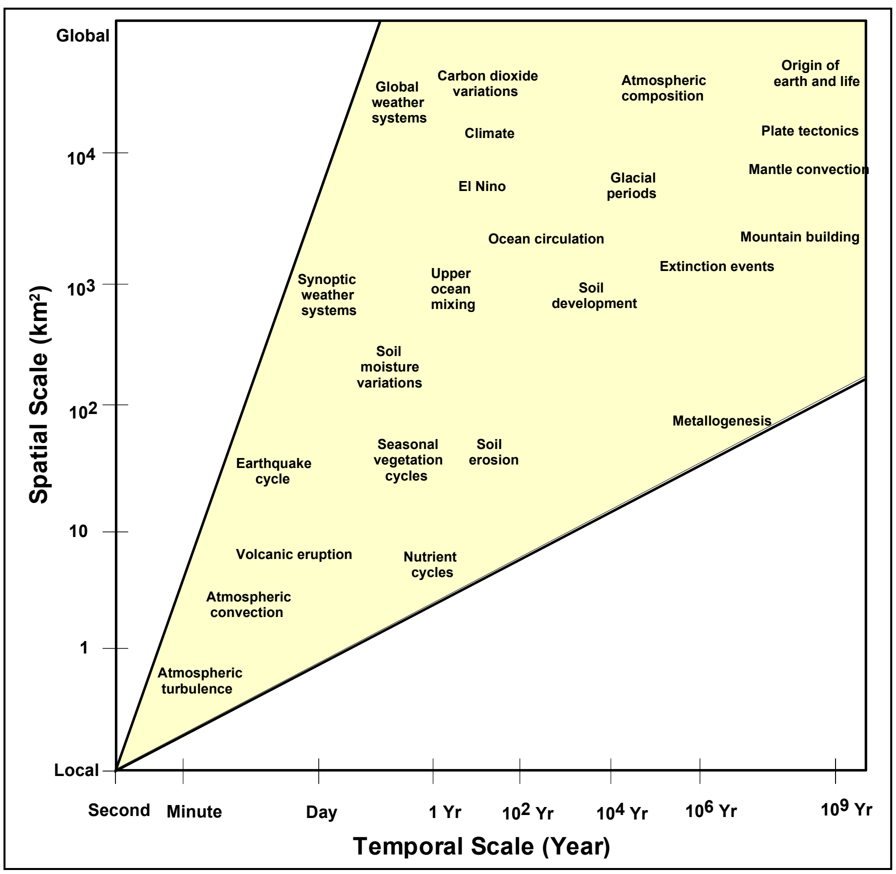


FIGURE C-1. Depiction of various physical and ecological phenomena. Adapted from NASA Advisory Council 1988.

C.2 Scale

Depending on the horizontal scale of interest, different atmospheric processes take on greater or less significance. For the atmospheric processes shown in figure 2, the horizontal scale of motion seems to be the better quantity to use for classification (Orlanski 1975). These scales are all interconnected. Large-scale atmospheric processes (e.g., climatic and daily synoptic weather systems) drive smaller scale processes as energy is transferred from large to small scales. Conversely, small-scale processes can organize to develop large-scale systems: for example, convective storms developing from smaller disturbances. Many of the cases of interest in ATD occur in the troposphere, the portion of the atmosphere up to 15 km above the ground. However, there are cases when transport and diffusion within the upper atmosphere are important (e.g., protecting air

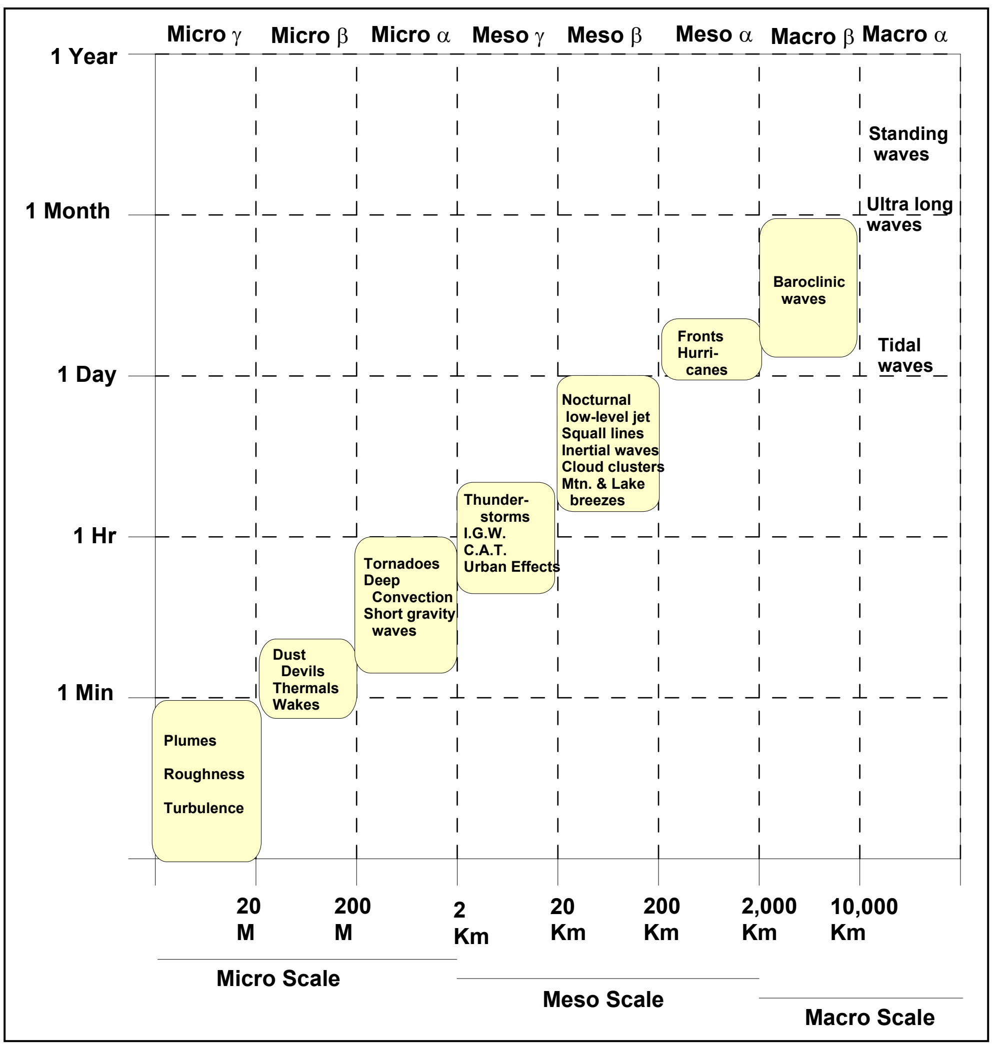


FIGURE 2. Scale definitions and different atmospheric processes with characteristic time and horizontal scales (adapted from Orlanski 1975). C.A.T is Clear Air Turbulence, and I.G.W. is Inertial Gravity Waves.

traffic from volcanic ash, tracking the path of materials from major explosions, or tracking the dispersion of materials originally constrained within the lower atmosphere but which slowly leak into the layers of air aloft).

The atmospheric boundary layer (ABL) is defined for the purposes of this discussion as the lower part of the atmosphere, which is directly influenced by the presence of the earth's surface during the diurnal cycle. This includes the diurnal evolution of solar heating and radiative cooling and the transitions between those states. For ATD, the three-dimensionality of the ABL is crucial to understanding the physics of its variability and, most important, for modeling the variability. With the exception of convective clouds, fronts, or terrain uplift, the troposphere above the ABL exhibits quasi-horizontal flow; vertical motions are slow and gradual. Within the ABL, the earth's surface, through heating and cooling the air and friction over various roughness elements coupled with sources and sinks of moisture, produces three-dimensional turbulence and intermittent processes, which seldom reach truly steady-state conditions. An integral aspect of this diurnal variation is that some of the material originally constrained in the lower atmosphere "leaks" into the layers of air above it. This leakage is accelerated by the action of deep convection, whether or not accompanied by clouds.

The upslope and downslope winds resulting from differential heating and cooling would not be explicitly treated in a model of ATD at the continental scale, but they would be of great concern if the scale were reduced to a local region. Mexico City is an example of a location where proper characterization of the interaction of local and mesoscale airflow circulation patterns is fundamental for proper characterization of transport and diffusion. Mexico City is located in a basin and is surrounded on most sides by hills and mountains. Observations and mesoscale analyses provide evidence that the local circulations are highly complex. A conceptual diagram depicting some of these processes is shown in figure C-3. Mexico City is not unique. Many major cities are located in valleys along major rivers, where upslope and downslope flows are common, or along shorelines of lakes and oceans, where land-sea breezes are common.

The choice of horizontal scale plays an important role in the formulation and selection of an atmospheric model. According to hierarchy theory, describing effects at some scale (the scale of interest) requires at least three levels (scales) for both comprehensiveness and conciseness: (1) the next smaller scale, which provides information up to the scale of interest, (2) the scale of interest, which constrains processes at the next lower scale and provides information up to the next larger scale, and (3) the next larger scale, which constrains processes at the scale of interest. At each scale, a decision must be made as to which physical processes will be represented and how explicitly each selected process will be treated. For instance, at a fine scale the potential evapotranspiration depends on physical parameters such as temperature, vapor pressure deficit, wind speed, surface roughness, precipitation, and soil moisture status, as well as biological parameters such as stomatal conductance (Monteith 1965). At subcontinental scales, Thornthwaite and Mather (1955) show that the potential evapotranspiration can be predicted adequately using a monthly mean temperature and precipitation and latitude (to determine length of day). The nature of the process has not changed with scale, but the relative contribution of explanatory variables has.

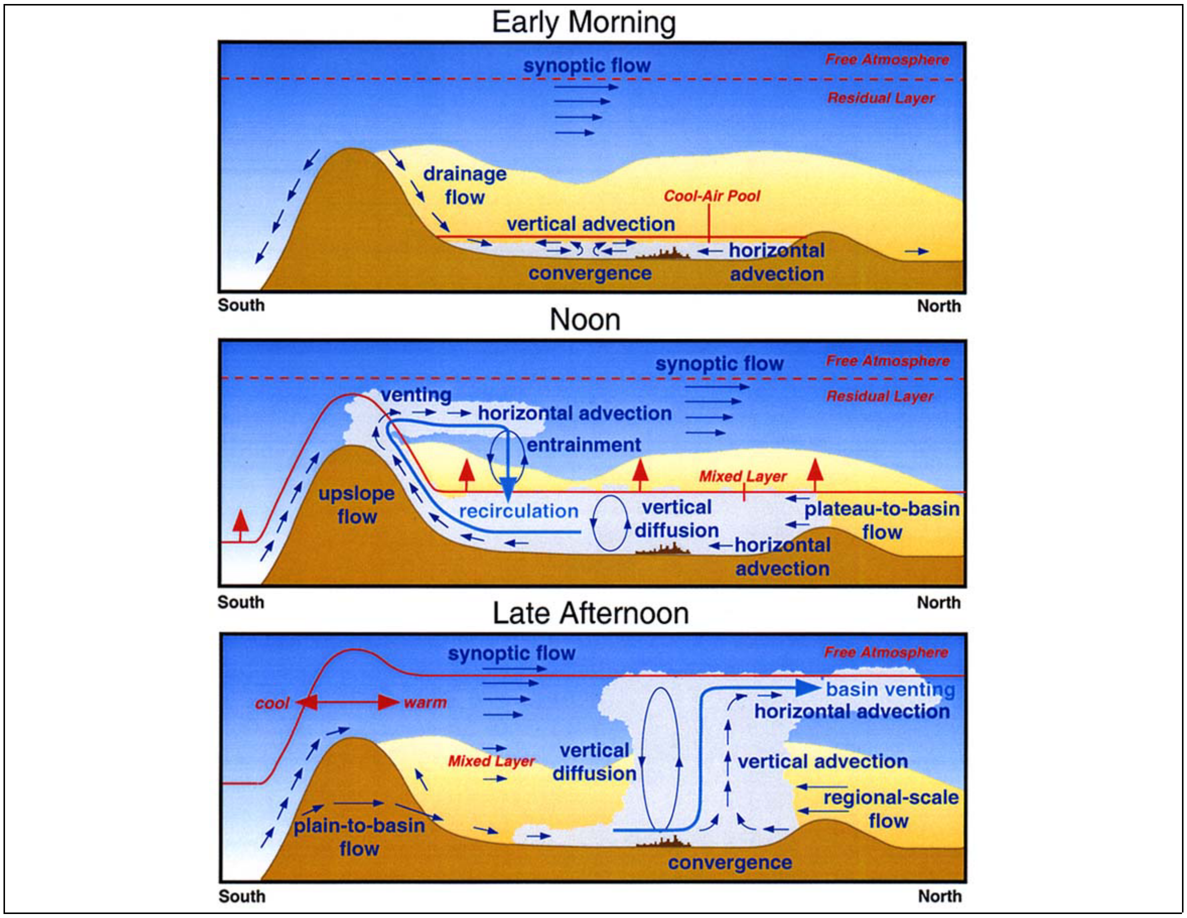


FIGURE C-3. Conceptual diagram depicting some of the meteorological processes associated with pollutant transport within the Mexico City Basin. (Contributed by Jerome Fast of Pacific Northwest National Laboratory, operated by Battelle Memorial Institute for the U.S. Department of Energy. http://www.pnl.gov/atmos_sciences/as_meso5.html.)

Aggregating a large number of processes or decomposing a complex system into a smaller number of levels is similar to approximating the solution of differential equations using a truncated Taylor series. The magnitude of the truncation errors depends on the nature of the processes (e.g., nonlinear interactions, feedbacks, and time delays), spatial heterogeneity, and the uncertainties of available model input and model parameterizations. Because of the feedbacks and interactions, it seems difficult to build a model that spans more than two orders of magnitude ("Carl Walters Rule of Thumb," personal communication from Dr. Gerry Peterson).

C.3 Predictability

A composite of the spectrum of horizontal kinetic energy in the troposphere is shown in figure C-4. In its average state, the atmosphere has a large amount of energy in long wavelengths and decreasing energy as scales become smaller. The energy spectrum (energy per unit wave number interval) decreases as wave number increases (wavelength decreases). The energy spectrum shown in figure C-4 encompasses six decades. As illustrated in figure C-2, the time scales of the motions compress and expand with spatial scale, so that in general, small-scale actions affect short time periods.

Numerical weather prediction models have been successful over the years because the kinetic energy spectrum decreases toward the smallest scale processes and the atmosphere is essentially a weakly stratified fluid, exhibiting quasi-horizontal flow. As computational facilities exploded in capacity and capability, operational weather models have successfully transitioned from the larger scale synoptic flows with horizontal grid sizes of ~200 km to more detailed mesoscale models with horizontal grid sizes of ~20 km or less and representation of terrain influences, oceanic interactions, vertical motions, and larger scale cloud systems. Research and operational models at Army test ranges go to smaller grid lengths (~ 1 km) and include more and more processes of cloud physics, radiative transfer, and land surface interaction and texture. As the grid size is decreased, time steps are decreased, and more details of the small scale processes must be accounted for within the model. From a simple theoretical construct, Lorenz (1969) estimates the spatial scales for loss of predictability as a result of small errors in a uniformly turbulent two-dimensional atmosphere. His results, shown in figure C-5, indicate that the predictability is lost after an hour or so for motions on scales below 40 km.

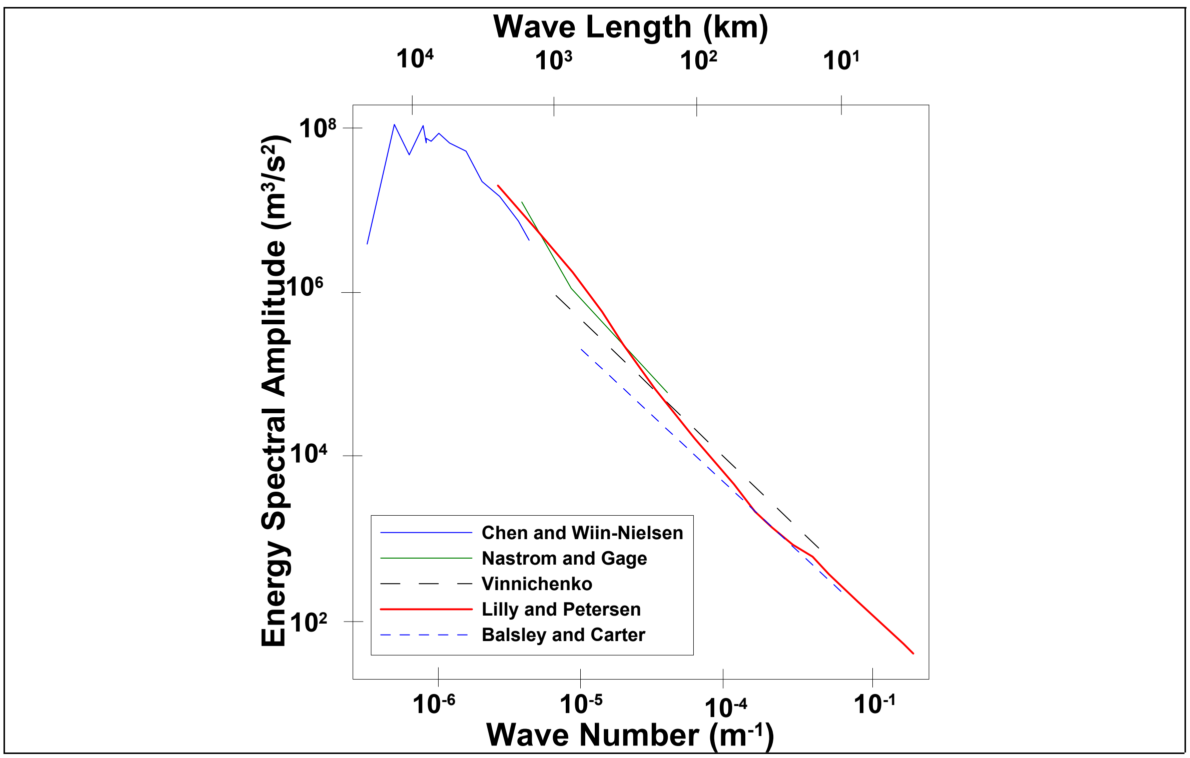


FIGURE C-4. Composite spectra of two-dimensional energy obtained from various sources. Adapted from Lilly 1985.

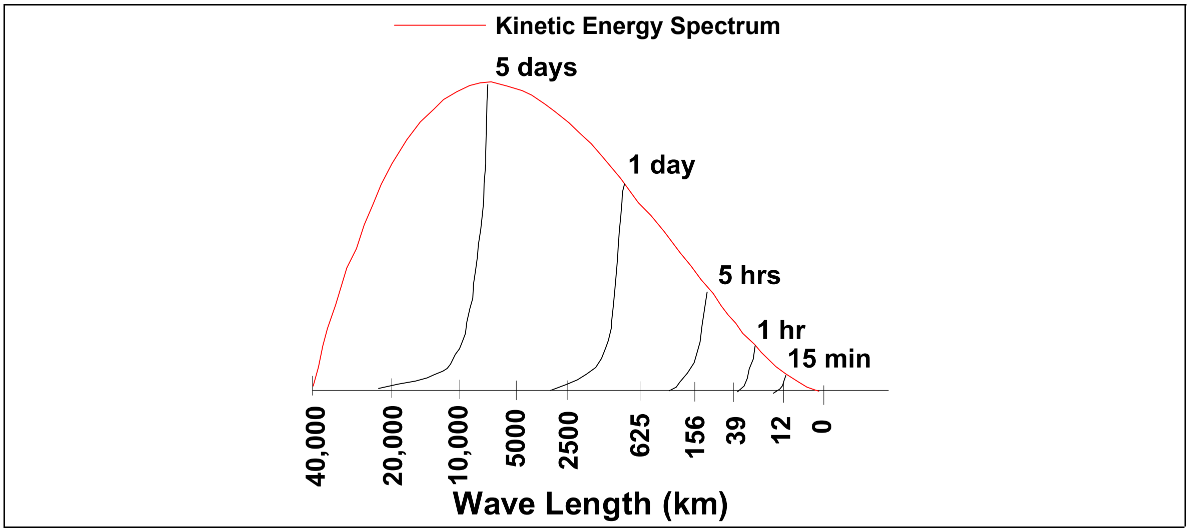


FIGURE C- 5. Results of a closure model calculation of the rate of loss of predictability of two-dimensional flow where the kinetic energy spectrum is given by the upper (red) curve. The short (black) parabolic areas show the left edge of the unpredicted spectrum as it proceeds to larger scales. Adapted from Lilly 1985 and Lorenz 1969.

Observations by Van der Hoven (1957) suggest that the spectrum of the intensity of horizontal wind fluctuations near the ground often shows a separation of scales, as in figure C-6. Large-scale motions of transient weather systems (highs and lows, fronts and storms) are at the left of the figure. A secondary peak representing diurnal processes occurs at about 12 hours. Processes of the order of an hour or so show little intensity compared with these longer processes or those with shorter periods (10 minutes, 1 minute). Although there is some scientific debate about the persistent presence of this "mesoscale gap," the data suggest that mesoscale models may be more effective in representing the larger scale processes than those at smaller scales.

The energetics of ABL turbulence scales are relatively small compared to larger scale flows. This means that these flows have less structure and change more rapidly than do larger scale flows. The memory time of the flow is short and the correlation times and lengths of ABL motions are small. To maintain predictability, high-resolution models may need to be refreshed more often with changing local conditions—insolation, winds, and surface moisture—at the scales of interest. Historically, these processes have been approximated by parameterizations using forecast values of larger scale flows. Where complex terrain is a dominant factor, this conventional thinking remains to be well tested and can be best considered a first approximation to be used with caution until better understanding develops. In anticipation of the discussion to follow, it should be emphasized that dispersion over cities can display the characteristics of severe terrain complexity.

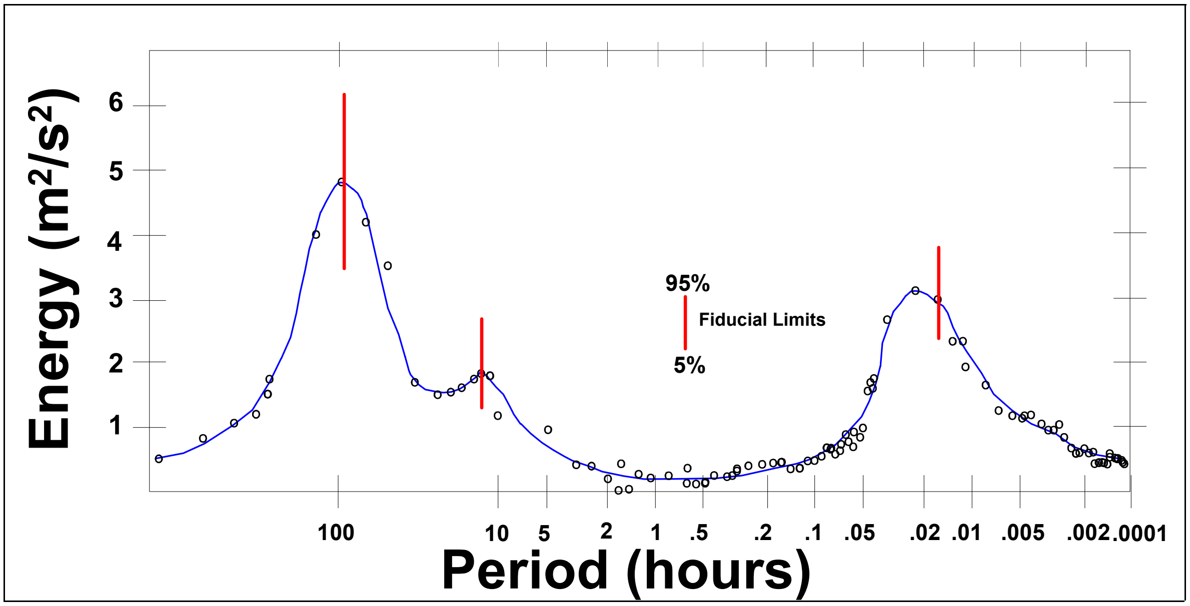


FIGURE C-6. Horizontal wind-speed energy spectrum at Brookhaven National Laboratory at about 100 m height. Data analyzed were collected during the period from June 1955 through February 1956. The statistical significance of the major peaks and gaps of the spectrum is shown by the 5% and 95% confidence (fiducial) limits. Adapted from Van der Hoven 1957.

As the scale of atmospheric motion becomes smaller, the effects of some processes become increasingly more difficult to treat explicitly or deterministically. Turbulence, the gustiness superimposed on the mean wind, can be visualized as consisting of irregular swirls of motion called eddies. Usually turbulence consists of many different size eddies superimposed on each other with different relative strengths. Compared with the other scales of meteorological motions, turbulence is on the small end of scale, as shown in figures C-1 and C-2. Phenomena such as turbulence with a spatial scale smaller than about 3 km and a time scale shorter than about 1 hour are classified as microscale. The small-scale phenomena associated with the microscale are so transient in nature that the deterministic description and forecasting of each individual eddy is virtually impossible (Stull 1988).

Physical models—such as wind tunnels, flow channels, and convection tanks—have been used successfully to investigate stochastic effects embedded within local-scale flows. These physical models have the distinct advantage of controlling boundary and initial conditions, high-resolution measurements, and repeatability. Such control permits a large ensemble of realizations and the potential for measuring inherent uncertainty. Figure C-7 illustrates how physical modeling results can be used to investigate the effect of temporal or spatial averaging. Vortex shedding from the corners of the building is apparent in the instantaneous pictures for both cases, but there is an obvious difference in the structure of the plumes. The tall building has a thin sinuous plume with much meandering, which is similar in some respects to the classical von Karman vortex street in the wake of a two-dimensional cylinder. This structure is not as pronounced in the wake of the wide building, which appears to have a more random internal structure (Lee et al. 1988).

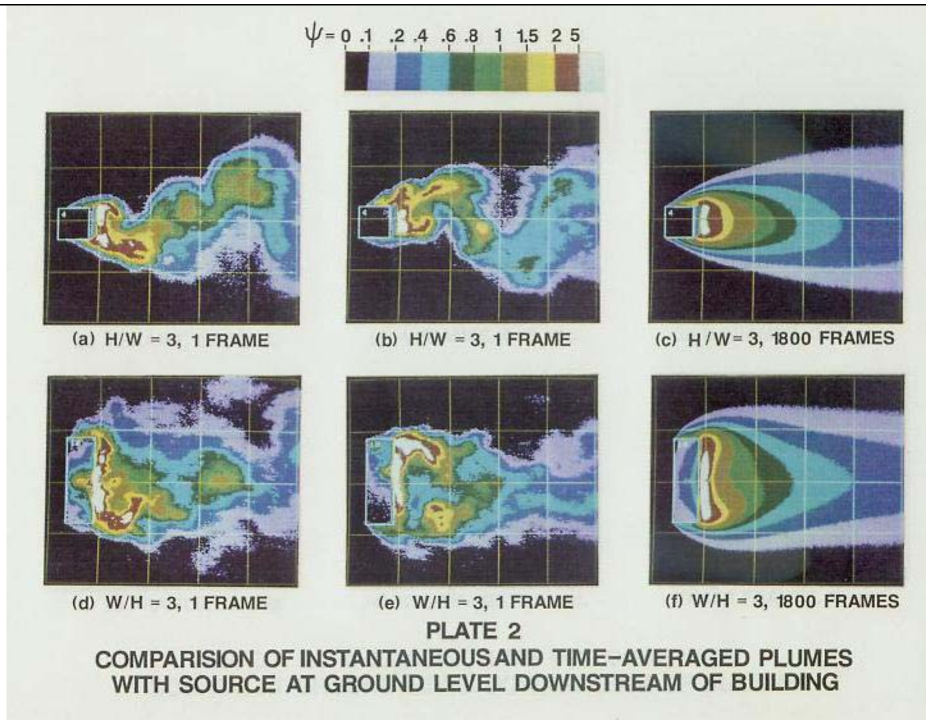


FIGURE C-7. A video image analysis of smoke concentration in wind tunnel flow fields (Lee et al. 1988). The smoke source is centered on the lee side of the building at the surface. The plate illustrates the very large differences between instantaneous and time-averaged plumes for a tall building, H = 30 cm, and a wide building, H = W = 30 cm, where W is the cross-stream width of the building. Photographs were collected at 30 frames per second. The relation between the digitized smoke intensity and the vertically nondimensional integrated concentration, ψ, of the smoke particles was obtained from calibration experiments in which the smoke was replaced by a mixture of ethane and air.

Most operational ATD models predict the ensemble mean transport and diffusion for the conditions specified. However, atmospheric releases are individual realizations from imperfectly defined ensembles. As illustrated in figure C-7, the within-ensemble variance of certain processes can be quite large. For instance, the first-order approximation of the lateral concentration profile of a plume is the often-assumed Gaussian shape. Inspection of tracer plumes reveals fluctuations superimposed on this Gaussian shape of the order of a factor of two. These fluctuations are not addressed or characterized in most operational transport and diffusion models (ASTM 2000). The approximation thus inherently constrains the predictability one can anticipate from such a model.

At the microscale, the direction of transport cannot be treated deterministically (Irwin and Smith 1984; Weil, Sykes, and Venkatram 1992), which precludes the possibility of simulating the concentration time series as would be seen at some fixed receptor location. In the simplest of circumstances, the microscale transport direction of a plume can be defined to about 25 percent of the overall width of the plume, which typically is on the order of 20 degrees in width. As the winds become light and variable, the uncertainty in the transport direction increases. At the microscale, the transport direction is best viewed as a stochastic variable having a large variance.

Only rarely is the centerline of a plume a straight line. In reality, because the initial plume dimensions are small in comparison with the length scale of the turbulence, the plume of dispersing material waves back and forth in a serpentine fashion in both the vertical and horizontal dimensions, as shown in figure C-7. The resultant plume meander contributes to the time-integrated plume spread but complicates determination of the time history of concentration values at some fixed point relative to the release point. The plume meandering causes the plume to be present at a given point only intermittently. A frequently cited model used for characterizing the process just described is the Gifford (1959) fluctuating plume dispersion model.

Further inspection of the crosswind profile of the instantaneous plume reveals that the vertical and lateral concentration profiles are not smooth bell-shaped curves but are "grassy-looking profiles, with many local deviations (greater and less) from the envisioned smooth bell-shaped profile." Various models have been proposed to characterize the combined effects of random concentration fluctuations within a plume that in turn is randomly varying (meandering). Wilson, Robins, and Fackrell (1982) note that the variance of the concentration fluctuations is seen to be strongly dependent on height above the surface, which "…can pose difficulties in hazard assessment because variations in receptor height of only a few meters cause significant changes in the predicted variance and thus the probability of observing a specified concentration."

C.4 Model Selection and Application

Part of the problem of model selection is knowing the horizontal scale of the various transport and diffusion processes of concern. Another part of the model selection problem is understanding which transformations and removal processes are of concern. Figure C-8, which depicts some of the major atmospheric processes typically addressed in transport and diffusion models, illustrates that not all processes are of interest at all scales. (Note that figure C-8 is not intended to provide guidance on when a process *must be* addressed.) For example, whether a model provides a means of characterizing buoyant plume rise is of no concern, even in the near field, unless the emissions are buoyant. Modeling systems that estimate the impacts of inert species typically focus on short transport distances where little dilution has occurred and concentration values are at their highest levels. Such models focus on characterization of diffusion, local flows, building effects, and initial source effects (e.g., buoyancy and explosive dispersal). Modeling systems that estimate impacts of chemical and radioactive species that form during transport are less concerned with microscale effects and are more concerned with mesoscale and macroscale processes. These models must address the consequences of variations in time and space of meteorological conditions that affect transport and diffusion.

Transport and diffusion models are typically employed for two circumstances: (1) for the assessment of near-field impacts from one or more releases (e.g., involving transport distances of 5 km or less), and (2) for the assessment of long-range impacts from a radioactive or very toxic release (e.g., involving transport distances of 30 km or more). In the first instance, where the plume dimensions are small in comparison to the dominant

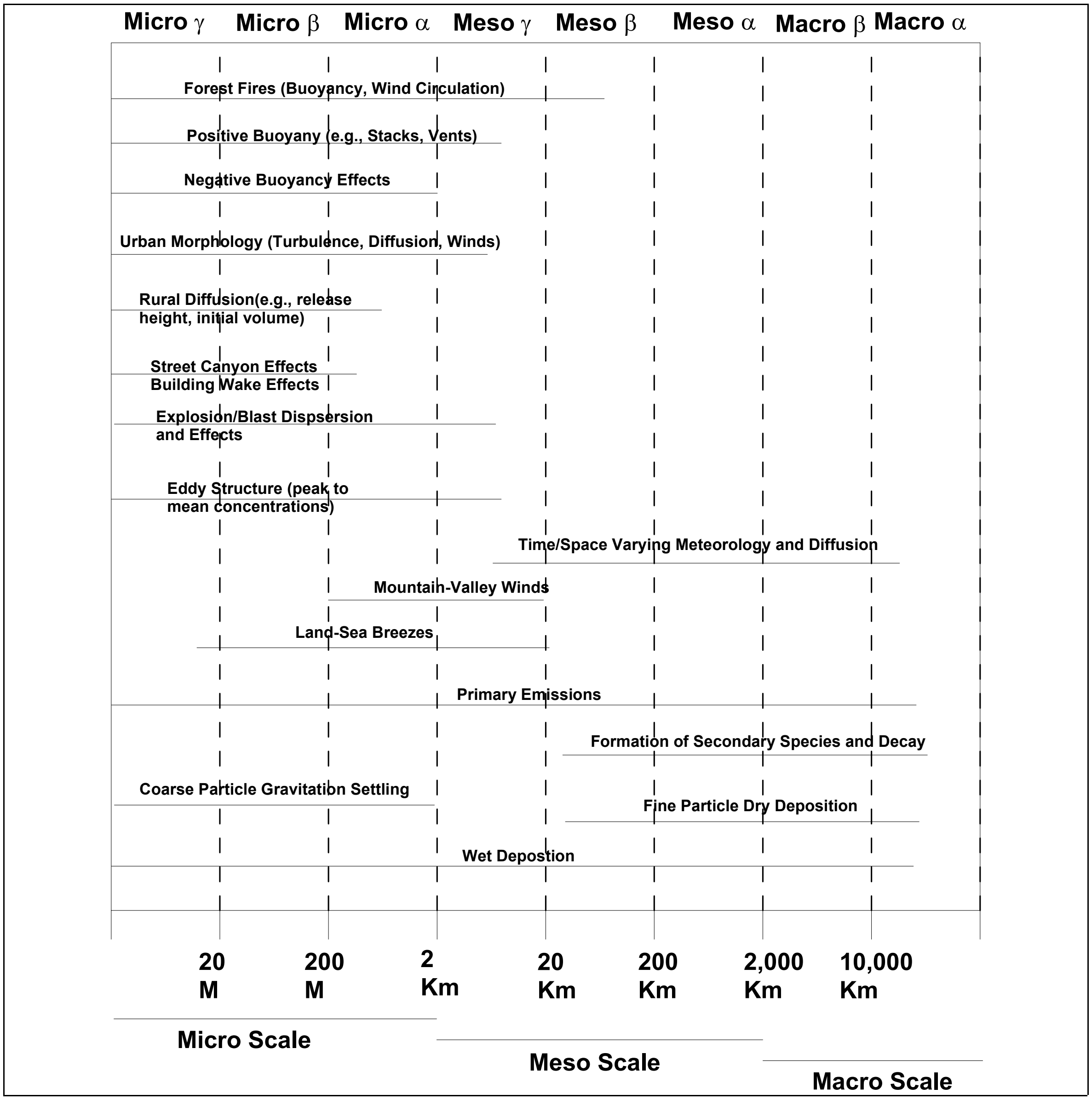


FIGURE C-8. Depiction of varying horizontal scale transport and diffusion processes likely to be of most concern.

turbulent eddy sizes, it will not be possible to simulate the actual transport explicitly. Turbulence and counter-gradient flows will make the near-field transport a highly stochastic process. For near-field impact assessment, the transport times are sufficiently short that the chemical/radioactive species being modeled can usually be treated as inert. In the second instance, the transport will still be uncertain but can be treated with more confidence. Counter-gradient flows are sufficiently short-lived that they can be neglected for longer-range transport problems. Whether the chemical or radioactive species can be treated as inert will depend on the species. As shown in Figure 8, many of the processes of interest for near-field impact assessment become of less importance for problems involving longer transport distances.

Most transport and diffusion models characterize emissions as coming from one of three source types: point, volume, or area. For any given application, the user must select the source type characterization that best represents those qualities of the release deemed to be most relevant to the questions being posed. Inevitably tradeoffs and compromises will be needed. Consider the situation depicted in figure C-9. This photograph of a point-source emission was taken in early morning, when there was significant buoyant rise and stable atmospheric conditions. The rising gases are stabilizing at different heights where there are significant differences in the direction of the transport winds. Do we simulate this as one plume or two plumes with different plume rises?

FIGURE C-9. Photo taken by Walt Lyons from his office window, which looks due south toward Denver, on a late spring day. (The year is uncertain but may have been 1997.) Contributed by Walter Lyons, President of FMA Research, Inc., Yucca Ridge Field Station, 46050 Weld County Road 13, Ft. Collins CO 80524.

For each source and source type, decisions have to be made as to the rate of release, the temperature of the gases (if hotter or colder than ambient temperature), and the initial dilution volume at the release—all of which may vary in time. For instance, the initial dilution and rate of release of emissions are critical if concentration values are desired close in to the release point, but the initial dilution is of less concern at distances much beyond 10 km downwind of the release. The successful application of a model is thus one of knowing what questions are being posed, what capabilities are present in the models, and what the tradeoff consequences are as one tailors the application of the model to a particular situation. We can envision a model as a tool that can be used in a variety of ways. To apply a tool successfully takes wisdom (i.e., experiential knowledge as well as academic knowledge). A hammer, a stone chisel, and a suitable block of marble in the hands of an experienced sculptor can create a statue, but in the hands of one who is not a sculptor (or an apprentice who is just learning the trade), just a pile of smaller stones.

Tennekes (1990) challenged the atmospheric modeling and measurement communities with three requirements:

- No observation is complete without an appropriately sampled estimate of the variance of the properties observed.
- No forecast is complete without a preceding estimate of forecast skill.
- No model calculation is complete without a calculation of its variance.

Taking all of the above aspects under consideration, one can conclude that the appropriate choice of an ATD model depends on five selection parameters:

- A definition (or redefinition) of the information to be gained or the decision to be made;
- The selection of the scale of interest;
- A knowledge of the physical processes that likely should be treated for the intended purpose;
- An appreciation of the uncertainty associated with the tradeoffs made in the model's construction; and
- The limits of predictability associated with any modeling system for the scale of interest.

C.5 General Model Types

Models of environmental processes are approximate representations of reality. Each model involves a set of tradeoffs, taking into account objectives such as whether it will be used to aid understanding, to estimate changes that might occur, or to determine where areas might be affected if a release were to occur. There are six general model types: plume, segmented plume and puff, Lagrangian particle, box, Eulerian grid, and computational fluid dynamics (CFD).

1. A **plume model** assumes that conditions are horizontally homogeneous (everywhere the same) and steady state as shown in figure C-10(B). As shown in figure C-10(A), plume models attempt to capture some essence of what is seen, but they make no claim to depict reality. Plume models are useful for quick estimates near a release, so long as the wind direction is relatively steady, the wind speed is greater than 1 to 3 m/s, and the distances downwind from the release are on the order of 20 km or less.

2. A **segmented plume and puff model** divides the emissions into a series of overlapping volumes (or puffs) so that one no longer need assume horizontal homogeneous conditions or require conditions to be steady state, as shown by the example in figure C-11. Developing the time- and space-varying meteorological conditions is resource intensive. These conditions include detailed terrain and land use data, meteorological observations from many locations within the domain, and a capability to model the local flows and circulations (either by dynamic or empirical models). Puff models have been used to study mesoscale transport and diffusion of species whose chemical or radioactive transformations can be represented using time-dependent decay approximations.

(A)

(B)

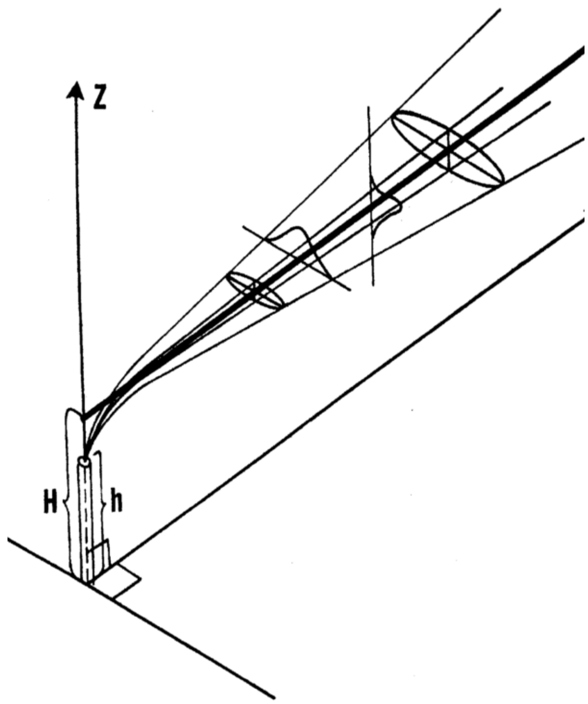
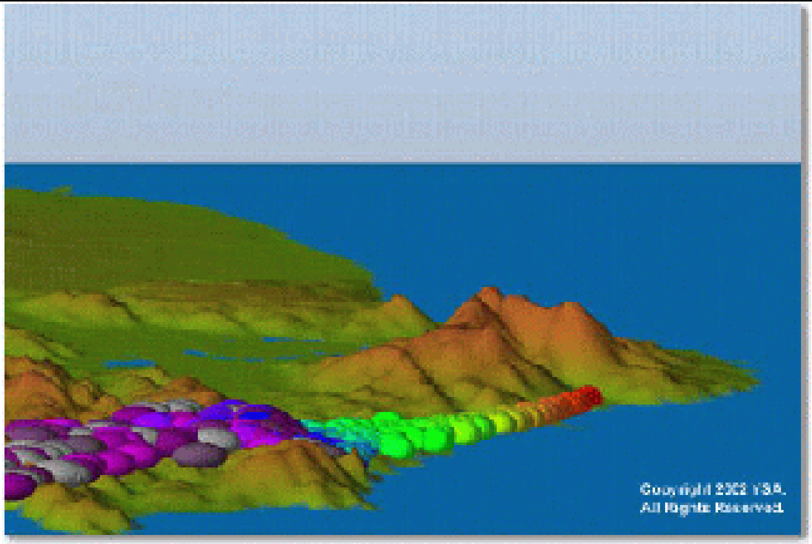


FIGURE C-10. (A) Diffusion of smoke from a tall stack during a sunny afternoon. (B) Idealization that would be used in a Gaussian plume model to characterize the diffusion from such a tall stack.

3. A **Lagrangian particle model** divides the emissions into thousands of tiny masses or particles that are individually tracked as they are stochastically transported downwind, as shown by the example in figure C-12. Each particle is "moved" at each time step by pseudo-velocities that take into account the three basic components of transport and diffusion: (1) the transport due to the mean wind, (2) the turbulent diffusion caused by the (seemingly) random fluctuations of wind components (both horizontal and vertical), and (3) the molecular diffusion (if not negligible). As shown by Hanna (1979), it is a plausible assumption to describe both Eulerian and Lagrangian wind vector fluctuations by a simple Markov velocity process (autocorrelation process of the first order). Particle models can be used to investigate



HOTMAC/RAPTAD simulation of pollutants over complex terrain

FIGURE C-11. HOTMAC/RAPTAD simulation of the transport and diffusion of pollutants over complex terrain. Contributed by Ted Yamada of YSA Corporation. Rt. 4, Box 81-A, Santa Fe, NM 87501.

and depict transport and diffusion within complex wind regimes (e.g., between buildings or during a frontal passage).

4. A **box model** assumes the modeling domain is one large homogeneous volume (box). Emissions entering this volume are assumed to be uniformly and instantaneously mixed throughout the volume (figure C-13). The top of the box may rise to simulate the rise of the mixing depth after sunrise, and pollutants above this rising lid could then be entrained into the volume. The location of the box can be stationary (to simulate the air over a city), or it can move with the transport wind (to simulate the "aging" of an air mass). Box models have been used to study photochemical problems and to compare alternative chemical kinetics.

5. An **Eulerian grid model** divides the world into a three-dimensional array of rectangular cells (grids) within each of which mixing is considered uniform and instantaneous. Grid models are used to simulate the formation of products through atmospheric chemistry and the removal of products by clouds and precipitation, all of which are usually sufficiently removed from the emissions of immediate concern that the "well-mixed" assumption in each cell is reasonable. Eulerian grid modeling systems have been used to study regional transport and fate of secondarily formed species (e.g., ozone, acid deposition, and fine particulate haze). Figure C-14 illustrates the application of the Community Model of Air Quality (CMAQ) to simulate the effect of reducing nitrogen oxide (NO_x) emissions by 50 percent. Results for ozone and particle matter (PM) with diameters less than 2.5 micrometers (PM2.5) are shown for the original base, the strategy simulation, and the difference (strategy minus base case) between the two for July 14, 1996, at 0100 GMT. Thus, negative

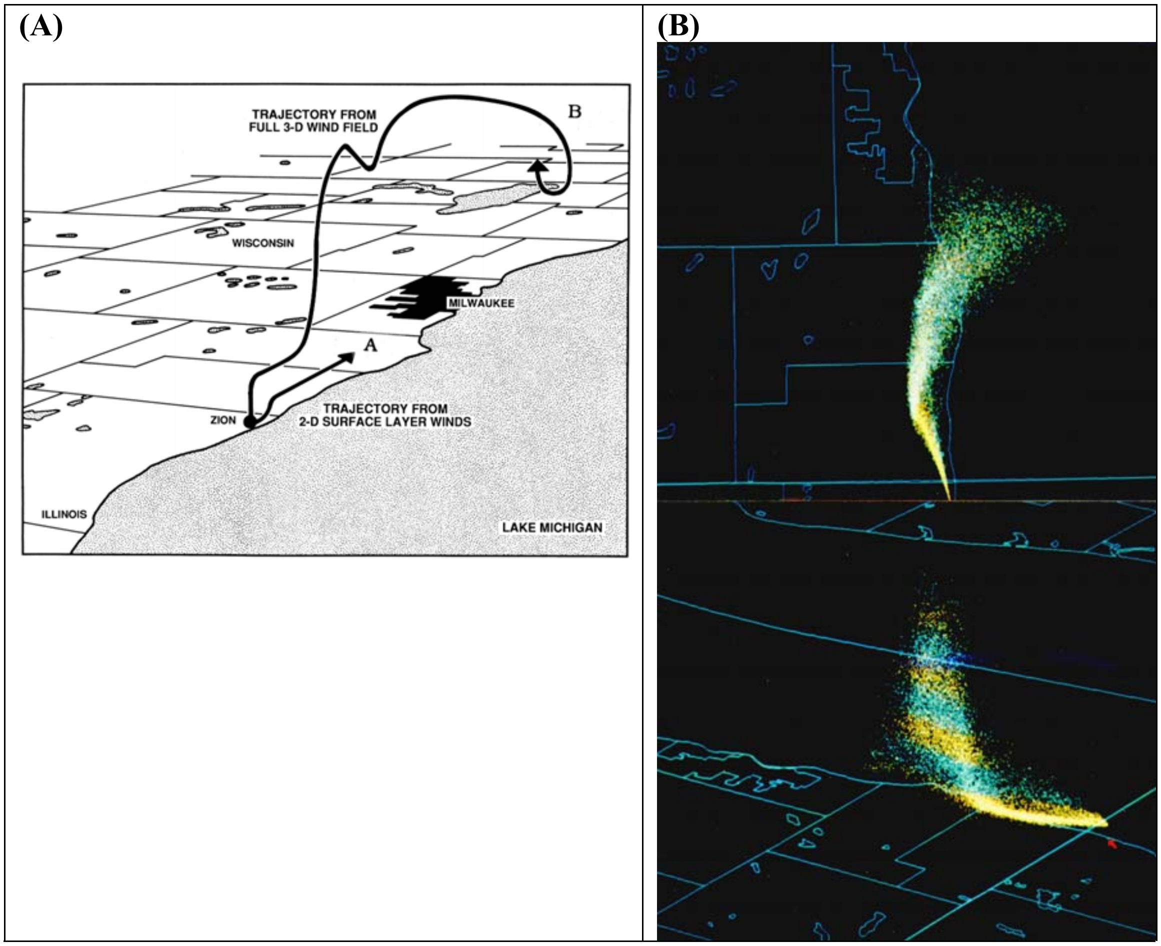


FIGURE C-12. (A) Typical plume trajectories calculated from RAMS output using only surface layer winds (trajectory A) which stays at 50 m altitude and the complete wind field (trajectory B) which rises to 1600 m altitude. (B, Top) Plan view of a simulated plume released from a 50 m high shoreline source into a weak lake breeze along the Lake Michigan shoreline. (B, Bottom) a perspective view of the plume from the southwest showing large quantities of the plume being transported vertically due to the strong upward motions in the lake breeze frontal zone. (Lyons et al. 1995; figures contributed by Walt Lyons.)

differences indicate decreases in ozone and PM2.5 levels, whereas positive differences indicate increases in the pollutants.

6. A **CFD** model is based on the three fundamental principles that govern the physical aspects of any fluid flow:
   - Mass is conserved.
   - Energy is conserved.
   - Newton's second law (the acceleration of an object is a function of the net force acting upon the object and the mass of the object).

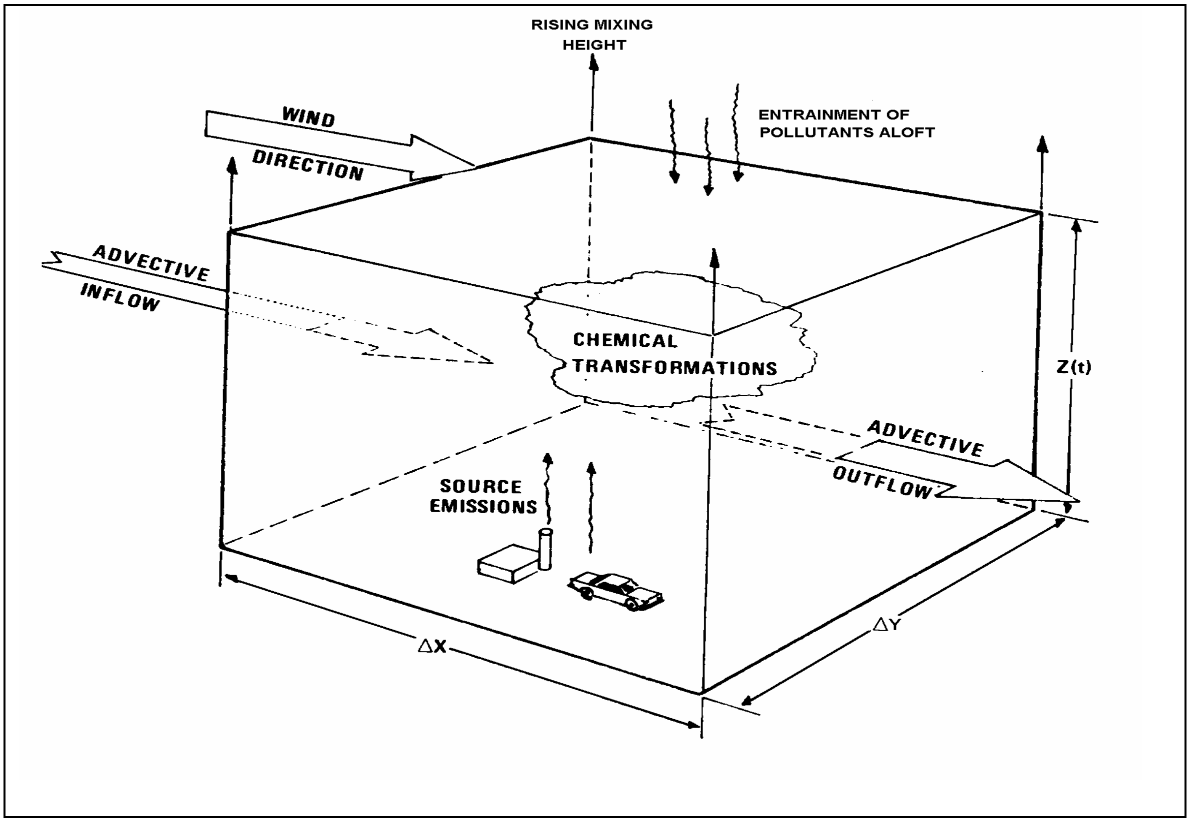


FIGURE C-13. Schematic illustration of a photochemical box modeling domain (Schere and Demerjian, 1984).

These fundamental principles can be expressed in terms of mathematical equations, which in their most general form are usually partial differential equations. CFD is the science of determining a numerical solution to the governing equations of fluid flow while advancing the solution through space or time to obtain a numerical description of the complete flow field of interest. The governing equations for Newtonian fluid dynamics, the unsteady Navier-Stokes equations, have been known for over a century. However, the analytical investigation of reduced forms of these equations is still an active area of research, as is the problem of turbulent closure for the Reynolds averaged form of the equations. For non-Newtonian fluid dynamics, the theoretical development of chemically reacting flows and multiphase flows is at a less advanced stage. CFD has been used to study flows around airplane wings and rockets, air flow through engine parts, and the transport and diffusion of particles around and between hills and buildings (e.g., figure C-15). To date the data requirements, problem definition, and time required to generate results have limited the use of CFD models to studies of special situations.

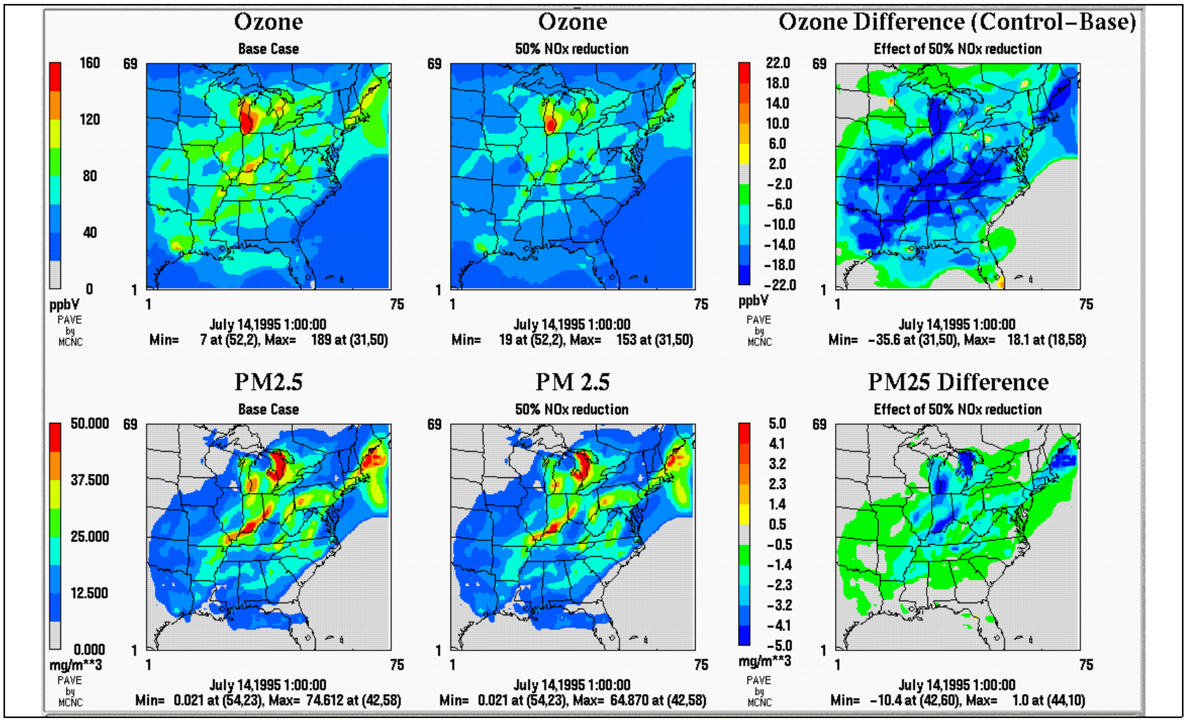


FIGURE C-14. Illustration of the effect of reducing NOx emissions by 50 percent, as computed by the Models3/CMAQ modeling system. “PM2.5” stands for “particle matter with diameter less than 2.5 µm. Source: Leduc, Schere, and Godowitch 2001.

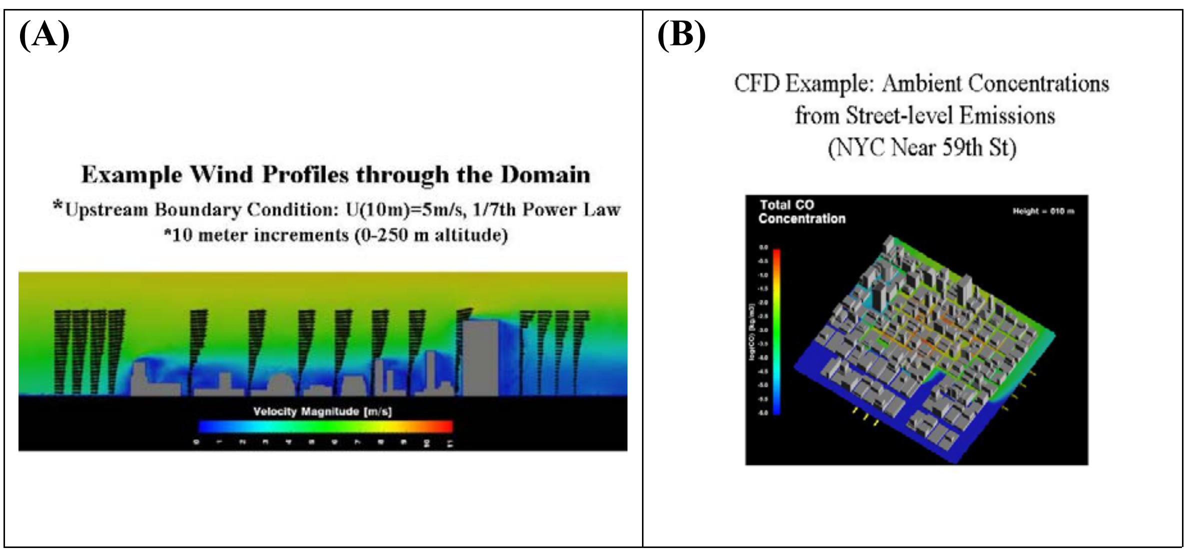


FIGURE C-15. Computational fluid dynamical simulation results for the adjustment of the wind profile to buildings associated with an urban domain (A) and a simulation of ambient carbon monoxide concentration values from street-level emissions (B).

C.6 Diffusion Characterizations

Any contaminant released into the atmosphere is transported by a variety of processes that can be defined generically as either advection or molecular and eddy diffusion (often referred to as turbulent dispersion). Advection is the movement of contaminants as a result of the mean flow. Molecular diffusion is a redistribution of mass (or energy) within a gas by Brownian motion and tends towards uniformity in mass (or energy). Brownian motion is thermal energy and results in random molecular collisions. There is motion in all directions, but there is a tendency for the mass (or energy) to move from areas of high concentration to areas of low concentration. Molecular diffusion is rarely of significance in comparison with eddy diffusion. Eddy diffusion results from turbulent velocity deviations from the mean flow. Turbulent deviations are mechanically generated by friction drag and flow through and around obstacles. Turbulent deviations can be enhanced or suppressed thermally by buoyancy forces arising from relative differences in temperature in air layers next to the ground or other surfaces. In this discussion, the term "diffusion" encompasses both molecular and eddy diffusion.

When reading the ATD literature, one can easily become confused by different usage of the terms "diffusion" and "dispersion." "Diffusion" is often used without mentioning whether it is meant to include both molecular and eddy diffusion. To further complicate matters, some texts use the term "dispersion" to refer to the combined effects of eddy diffusion and advection, whereas other texts use the term "dispersion" in the sense of "turbulent dispersion" but without the qualifier "turbulent." For the sake of clarity, this discussion avoids use of the term "dispersion." It uses "diffusion" to refer to the combined effects of molecular and eddy diffusion.

There are two other considerations to be recognized in characterizations of eddy diffusion. First, there is an implicit averaging time assumed, which is associated with the definition of the "mean flow" of the atmosphere. In atmospheric transport and diffusion models, the mean flow is typically defined at 1-hour intervals, but this choice is not mandated. If the mean flow is defined at 5-minute intervals, then a portion of what would have been characterized as eddy diffusion for 1-hour intervals will instead necessarily be characterized by the time and space variations in the 5-minute mean flow. Second, not all deviations from the mean flow are random; hence, not all eddy diffusion is random. The thermal eddies of a convective boundary layer transport mass from the surface to the top of the convective boundary layer in an organized manner. This convective eddy transport could be thought of as advection, but since it occurs in less than 1 hour and cannot be simulated deterministically, it is typically viewed as a component of eddy diffusion.

C.6.1. Empirical Characterizations of Diffusion

There are many instances when field-data observations of smoke and tracer diffusion have been organized into empirical schemes for the characterization of diffusion. Typically, these schemes rely on the empirical observation that the vertical and lateral crosswind concentration distribution appears to be similar to a Gaussian shape. Hence, these schemes provide characterizations of the vertical and lateral Gaussian parameters (as a function of travel time or distance of transport, stability, and roughness length of the surface). The well-known Pasquill-Gifford diffusion parameters (Pasquill 1961; Gifford 1961) have been used extensively in many of the popular transport and diffusion models. The Pasquill-Gifford diffusion parameters were derived from various experiments over rural terrain. The lateral diffusion parameters have an implied averaging time of 3 minutes and a roughness length of 3 cm for transport distances less than 1 km. For transport greater than 10 km, the lateral diffusion parameters still have an implied averaging time of 3 minutes but a roughness length of 30 cm. The vertical diffusion parameters are likely appropriate for all averaging times up to 30 minutes and have the same variation in roughness as the lateral diffusion. Field studies conducted in the 1960s in St. Louis, Missouri, by McElroy and Pooler (1968) included observations of a tracer released and sampled for 1-hour periods. Their results have been used to develop a characterization of diffusion for urban environs. There are many such studies (Randerson 1985); however, the important consideration in the use of any of these schemes is to recognize that they may be relevant only for the circumstances under which the data were collected.

C.6.2 Similarity Theory and PBL Parameterizations

Useful schemes for the characterization of diffusion have been fashioned though an analysis of field studies of diffusion that incorporate known important variables and governing "scaling" parameters. Such models are called similarity models because they imply "similar" behavior of the atmosphere from one place or time to another, if one assumes that certain scaling parameters are held constant. The important scaling parameters in surface-layer similarity models of diffusion are L, u*, and z_o, where L is the Monin-Obkhov length, u* is the friction velocity, and z_o is the surface roughness length. Examples of surface-layer similarity models of diffusion are provided by Briggs and McDonald (1978); Horst, Doran, and Nickola (1979); and Briggs (1982). The surface layer is nominally the lower of |L| or Zi/10, where Z_i is the mixing height. Scaling parameters for convective diffusion models are L, Z_i, and w*, where w* is the convective velocity scale. Examples of convective diffusion models are Weil and Furth (1981), Misra (1982), and Venkatram (1983).

C.6.3 Statistical Characterizations of Diffusion

Taylor's (1921) theory for homogeneous and stationary turbulence has served as the basis for several statistical models of atmospheric diffusion. These models imply that the spread is linear with time in the near field, and proportional to the square-root of time in the far field. The transition from near field to far field is typically specified in terms of a Lagrangian time scale. Examples of statistical theory for the characterization of the vertical or lateral extent of a release as it is transported downwind are Draxler (1976) and Venkatram, Strimaitis, and DiCristofaro (1984). The Monte Carlo particle trajectory models of diffusion are statistical characterizations of diffusion.

C.6.4 First- and Second-Order Closure Assumptions

Gradient transport (K-theory) models are derived from the continuity equation with the turbulent fluxes of concentration (C) assumed to be proportional to the mean gradient of C, with K being the constant of proportionality. This is called a "first-order closure" assumption because it retains the prognostic equations for only the zero-order mean variables and parameterizes the turbulent fluxes. K-theory models are typically used with grid models, where the emphasis is often on atmospheric chemistry and regional transport. An important consideration is that gradient transport models of diffusion have implicit time and space scales. The mean wind components represent averages over some time scale and space scale. Velocity fluctuations with time and space scales less than those implicit in the mean wind components are considered turbulence. Therefore, they are implicitly included in the proportionality constant K. However, as discussed by Taylor (1921), the rate of diffusion of a plume depends on the plume size. This limits the applicability of K-theory models of diffusion to instances where the size of the plume is greater than the size of the dominant turbulent eddies so that all of the turbulence implicit in K is taking part in the diffusion. The vertical diffusion of point sources can be modeled using K-theory for sources near the ground, where the turbulent eddies are sure to have scales less than the thickness of the plume. However, K-theory can be used to model elevated releases only when the vertical extent is spread out over several hundred meters (Hanna, Briggs, and Hosker 1982).

There are "higher-order" closure assumptions (e.g., second-order) where the prognostic equations are retained for both the mean and the flux variables and the third moments are parameterized. Second-order closure has been used to develop plume models (Sykes Lewellen, and Parker 1986) and puff diffusion models (Sykes and Henn 1995).

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APPENDIX D. ACRONYM LIST

24/7	24 hours per day, 7 days per week
ABL	atmospheric boundary layer
ACARS	Aircraft Communications Addressing and Reporting System
AEC	Atomic Energy Commission
AFWA	Air Force Weather Agency
ALOHA	Areal Locations of Hazardous Atmospheres [an ATD model]
AMS	Aerial Measuring System [a NIRT asset]
ARAC	Atmospheric Release Advisory Capability
ARL	Air Resources Laboratory [of NOAA]
ASMD	Atmospheric Sciences Modeling Division [of NOAA/ARL]
ATD	atmospheric transport and diffusion
CAMEO	Computer-Aided Management of Emergency Operations [software system]
CBNP	Chemical and Biological National Security Program
CBRN	chemical, biological, radiological, or nuclear
CBRNE	chemical, biological, radiological, nuclear or high-yield explosive
CFD	computational fluid dynamics
CD-ROM	compact disk–read-only memory
CMAQ	Community Model for Air Quality
CMAT	Consequence Management Advisory Team
CSEPP	Chemical Stockpile Emergency Preparedness Program
CTM	chemical transport model
DAS	data assimilation system
DOE	Department of Energy
DHS	Department of Homeland Security
DNA	Defense Nuclear Agency
DNS	direct numerical simulation
DOD	Department of Defense
DTRA	Defense Threat Reduction Agency
EPA	U.S. Environmental Protection Agency
EP&R	Emergency Preparedness and Response [Directorate of DHS]
ESSA	Environmental Sciences Services Administration
FCMSSR	Federal Committee for Meteorological Services and Supporting Research
FEMA	Federal Emergency Management Agency
FRMAC	Federal Radiological Monitoring and Assessment Center
GMU	George Mason University
GIS	geographical information system
GPS	Global Positioning System
HAZMAT	hazardous material
HMRD	Hazardous Materials Response and Assessment Division [of NOAA]

HPAC	Hazard Prediction and Assessment Capability
JAG	Joint Action Group; unless otherwise qualified, the JAG/ATD(R&DP), which is the author of record of this R&D plan.
JAG/ATD(R&DP)	Joint Action Group for Atmospheric Transport and Diffusion Modeling (R&D Plan)
JAG/SEATD	Joint Action Group for Selection and Evaluation of Atmospheric Transport and Diffusion Models
JEM	Joint Effects Model
JTF-CS	Joint Task Force for Civil Support
LES	large eddy simulation
LFA	lead Federal agency
LINC	Local Integration of NARAC with Cities
LLNL	Lawrence Livermore National Laboratory
LOE	level of effort
MAC	Mapping Analysis Center
MADONA	Meteorology and Diffusion over Non-Uniform Areas [field study]
METOC	Meteorology and Oceanography [U.S. Navy]
METREX	Metropolitan Tracer Experiment
MOA	memorandum of agreement
MUST	Mock Urban Settings Test
NARAC	National Atmospheric Release Advisory Center
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NIRT	Nuclear Incident Response Team
NNSA	National Nuclear Security Administration
NOAA	National Oceanic and Atmospheric Administration
NORTHCOM	U.S. Northern Command [of DOD]
NRC	Nuclear Regulatory Commission
NTS	Nevada Test Site
NWP	numeric weather prediction
NWS	National Weather Service of the National Oceanic and Atmospheric Administration
OFCM	Office of the Federal Coordinator for Meteorological Services and Supporting Research
OSE	observation system experiment
OSSE	observation system simulation experiment
OWS	Operational Weather Squadron
QA/QC	quality acceptance and quality control
R&D	research and development
RAP	Radiological Assistance Program
RDT&E	research, development, test, and evaluation
READY	Realtime Environmental Applications and Display System
SBIR	Small Business Innovative Research
SBL	stable boundary layer

SDO	standard development organization
SORD	Special Operations and Research Division [of NOAA/ARL]
STTR	Small Business Technology Transfer [program]
UAV	unmanned aerial vehicle
VTMX	Vertical Transport and Mixing [field program]
WMD	weapons of mass destruction
WRF	Weather Research and Forecasting [model]
WSR-88D	Weather Service Radar 1988, Doppler (also Doppler Weather Radar; NEXRAD)

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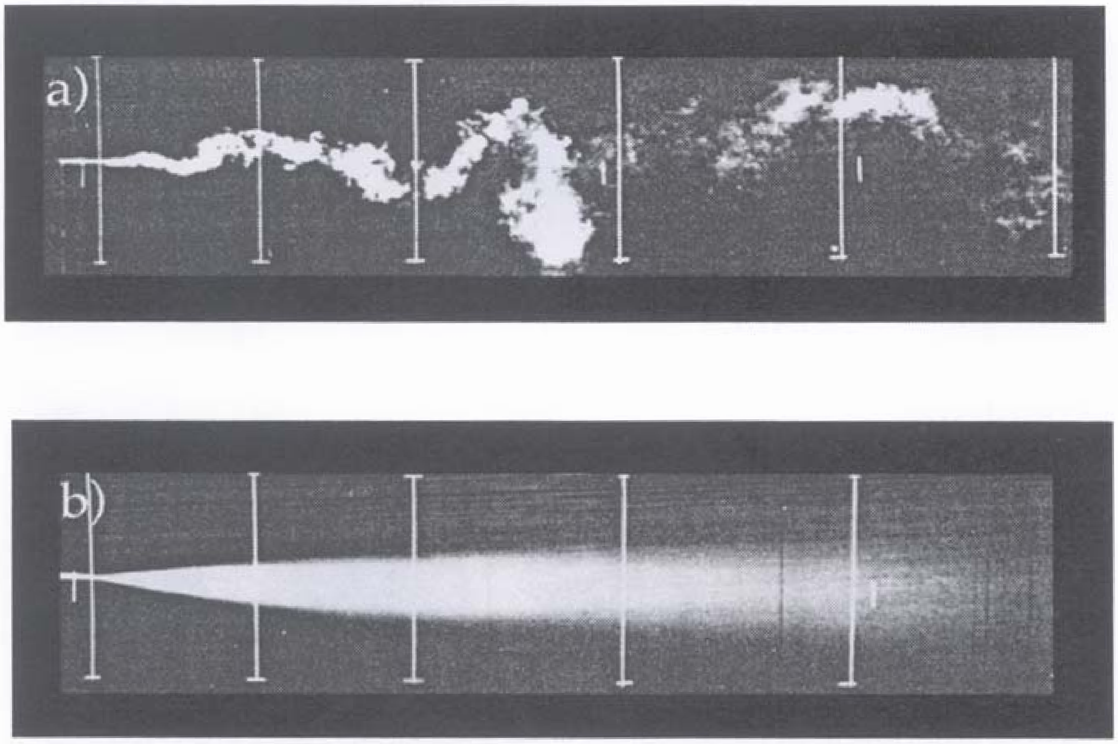

Two images of the same release. In (a) we see a photograph of an instant during a point source release of smoke within a wind tunnel (view is taken looking down on the plume), where large and small swirls have distorted the plume into serpentine twists and turns. In (b) we see a time-average photographic exposure of the smoke release, where the time-average of the individual chaotic swirls are seen to have the "traditional" Gaussian plume shape used in ATD plume dispersion models. (Photographs are courtesy of U.S. EPA/NOAA Fluid Modeling Facility).

Model of World Trade Center site, Manhattan, New York City in the U.S. EPA/NOAA Fluid Modeling Facility.