SECOND COMMENT BY JIM LONG OPPOSING SPECIAL EXCEPTION #1378

Charles County Board of Appeals
c/o Carrol Everett
200 Baltimore St
La Plata MD 20640

December 5, 2017
via email: EverettC@charlescountymd.gov

Re: Docket #1378, Charles Station Compressor application for Special Exception

Dear members of the Board of Appeals:

Here I point out that the unique location of Charles Station within the Mt. Vernon viewshed may needlessly increases ground-level air pollution by forcing the smokestack height to be lower than necessary. The problem is exacerbated by uncertainties in the modeling of air-pollution concentrations, some of which are associated with the specific location near a tall forest, and near to the hillside defining the Potomac River floodplain.

Dominion proposes to burn natural gas to drive two large compressors with a total capacity exceeding any in New York state.[1] Two 50-foot tall stacks would disperse the combustion products, many of which are toxic. A stack's height is the first line of defense against the ground-level air-pollution—a taller stack reduces the ground-level concentrations (Fig. 1)[2]. At the October 24 hearing, Joshua Kauffman testified he had learned that Dominion lowered its intended stack height after consulting with Mt. Vernon. If this is so, the ground level concentration of pollutants is higher than need be *by virtue of the location of the compressor station.*

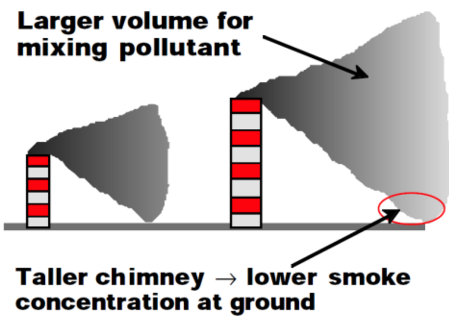


Figure 1 Image from UCLA course notes (Ref. 2)

Even if the stack height was not lowered by request of Mt. Vernon, the chosen 50-foot height is substantially lower than Good Engineering Practices (GEP) would allow. The EPA limits the height of a stack to that given by a GEP formula. This height-limit avoids reducing ground pollution below air-quality-standards by merely increasing stack height, a practice that can lead to excessive overall pollution of the atmosphere. At the same time, winds around nearby structures can create downwash, which increases ground-level pollution (Fig. 2b).[3] The GEP formula computes a height tall enough to reduce the likelihood of problems due to downwash.

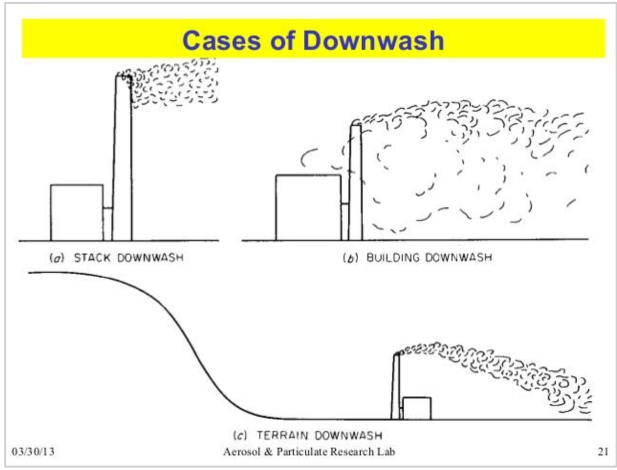


Figure 2 Examples of downwash from Ref. 3

In its application to FERC,[4] Dominion explains that the EPA's GEP formula leads to stacks 83 feet tall if the compressor building is 33 feet tall. However, at the July 11 hearing during cross examination of Dominion's witness James Jacobs, it was divulged that 33 feet referred to the building's *eve* height, whereas the *peak* would be 45 feet. Applying the GEP formula to a building 45 feet high yields a stack height of 113 feet, more than double the proposed height.

The EPA permits smaller heights if the applicant—using EPA approved computer modelling—computes ground-level pollutant concentrations to be less than air-quality standards. However, in the words of one expert:[5]

> "*Air dispersion modeling is more art than science. As with all art, skill and experience determine the value of the result*."

Modelling uncertainties. The proposed 50-foot stacks are considerably smaller than the rule-of-thumb GEP formula computes (either 83 feet or 113 feet depending on the assumed building height). The short stack increases the likelihood that uncertainties might in reality increase pollution concentrations beyond those computed. In fact, quite large modeling uncertainties are acknowledged by the EPA:[6]

> "(1) Models are more reliable for estimating longer time-averaged concentrations than for estimating short-term concentrations at specific locations; and (2) the models are reasonably reliable in estimating the magnitude of highest concentrations occurring sometime, somewhere within an area. For example, errors in highest estimated concentrations of ± 10 to 40 percent are found to be typical *i.e.*, certainly well within the often quoted factor-of-two accuracy that has long been recognized for these models.

With typical errors of up to 40%, what is one to make of the fact that the plant *would emit NO_2 to within only 6% of the regulated maximum for the one-hour average concentration*? [7]

Use of a remote airport as a source for meteorological data lends uncertainty

In computing pollutant concentrations emitted from the flue-stacks, various meteorological conditions, like temperature and wind speed and direction, are fed into a computer model (AERMOD, AIRMET). Meteorological data from Reagan National Airport is used because it has the requisite density of data needed by the models. National Airport is located 13 miles north of the compressor station and within the heat-island of Washington D.C. This raises at least two uncertainties regarding (i) temperature and (ii) wind speed and direction.

<u>**Temperature**: low values are more common at closer Ft. Belvoir than Reagan National</u>:

Pollutant concentrations tend to increase in colder weather. When modeling the concentration of the pollutant NO_2, Dominion rejected subzero temperatures because "these conditions are extremely limited annually." [8] While cold temperatures may be unusual at Reagan National, where Dominion's modeling data originated, they are much more common at Ft. Belvoir's

Davison Field, which is 7 miles closer to the compressor station (Fig. 3). I have compared the temperatures between the two airports over the ~13 year period from 1957 through 1970 (the only period for which I could find daily temperatures at *both* airports). In this period, Reagan National had *zero days* with temperatures below 0 Fahrenheit, while Davison Field had *17 days* with sub-zero temperatures.

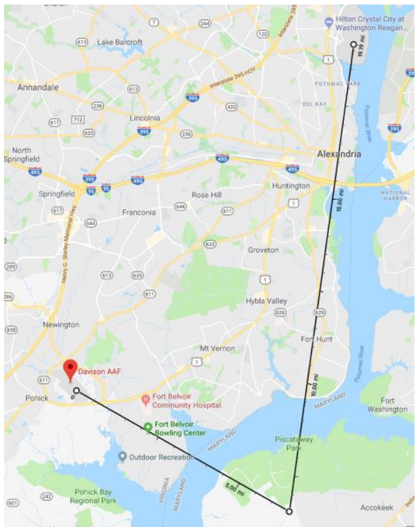


Figure 3 Location of the proposed compressor station relative to Reagan National Airport (the source of weather data for modeling), and Davison Field at Ft. Belvoir.

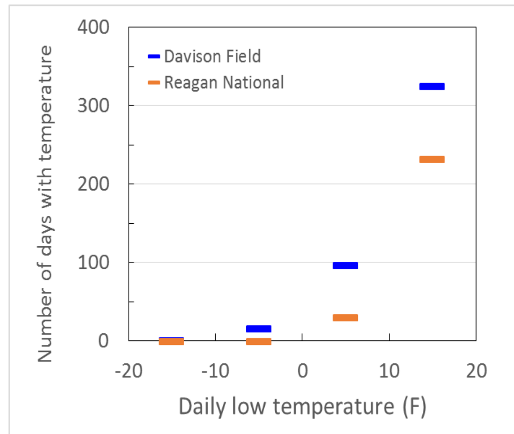


Figure 4 Each symbol gives the number of days within a temperature “bin” ten degrees wide. The first bin is from -20.1 to -10 F. Davison Field is colder than Reagan National.

The much greater frequency of low temperatures at the closer airport is evident in Fig. 4. This histogram shows the number of days within a given band of daily low-temperatures, each 10 degrees wide. For example, in the 13 year period analyzed, Davison Field had nearly 100 days with a low temperature between 0 and 10 F, whereas Reagan National had only 30 days. These results show that that the proposed site for the compressor likely experiences colder temperatures than were used in the computer modeling of ground-level pollution. Hence confidence in the computed concentrations produced by Dominion is undermined, and in a direction indicating more pollution than computed because of the lower local temperatures.

Wind: directional wind patterns differ substantially between the two airports

Figure 5 presents the probability distribution for winds blowing from a certain direction of the compass for both Davison Field and more remote Reagan National.[9] Data were averaged over nearly eight years from 2010 through 2017. The wind patterns differ substantially. It is clear that relying on weather data from National Airport for pollution modelling introduces what appears to be significant uncertainty in the results because the wind patterns are quite different closer to the station.

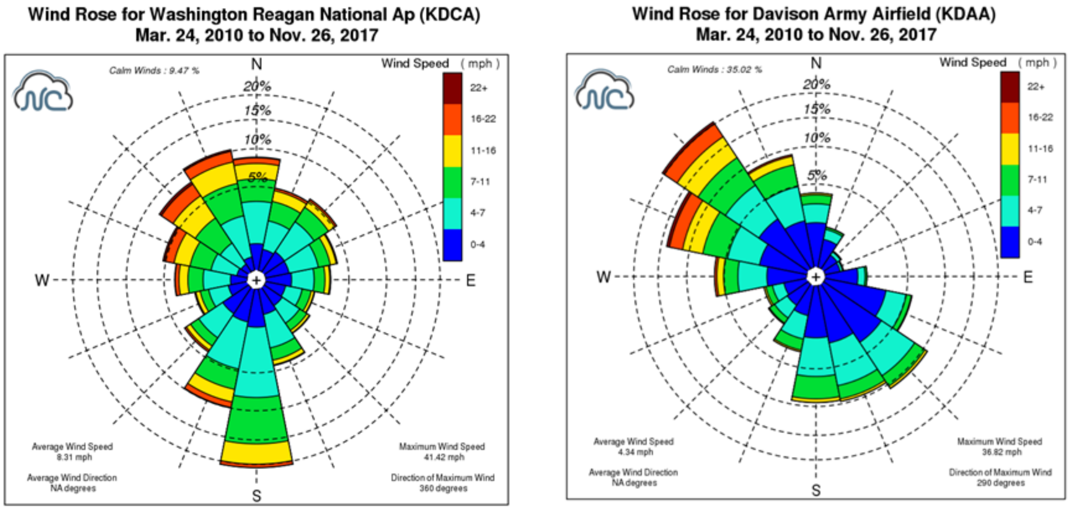


Figure 5 Comparison of wind patterns showing the substantial difference between Reagan National Airport, the source of wind data in the pollution computer modelling, and Davison Field which is 7 miles closer to proposed compressor station.

Topology:

The compressor station is located near an escarpment that defines the Potomac River's greater floodplain, pictured in Fig. 6. The red line runs from the station, marked by a red diamond, up over the dense contour lines defining the escarpment. The elevation profile along the red line is shown in Fig. 7 approximately to scale. In Fig. 7, a stack is indicated in red and is shown at its approximate height. A forest canopy comes to within about 200 feet of the stack, a dimension I inferred from the plan view of the site.[10] The canopy height is assumed to be roughly 70 feet, but is likely taller.

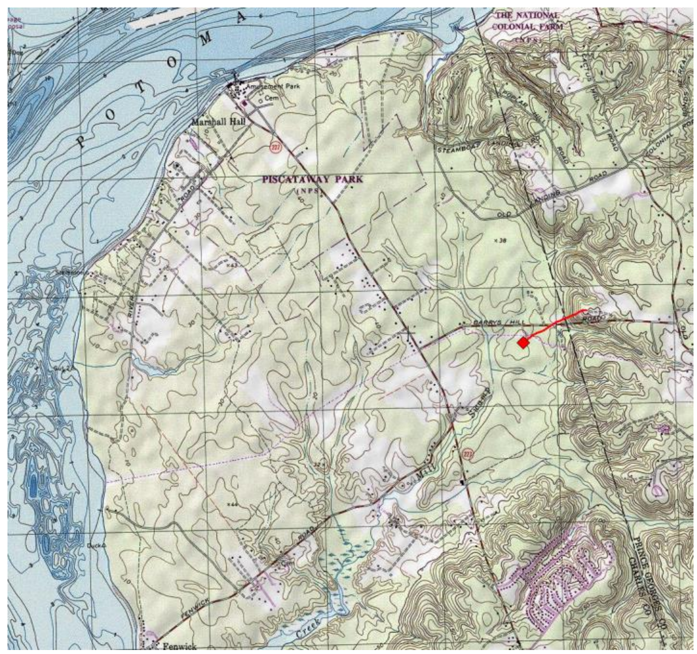


Figure 6 USGS topo map showing relation of compressor station (red diamond) to the surrounding hillsides (dense contour lines). Red line shows the transect corresponding to the elevation profile of Fig. 7.

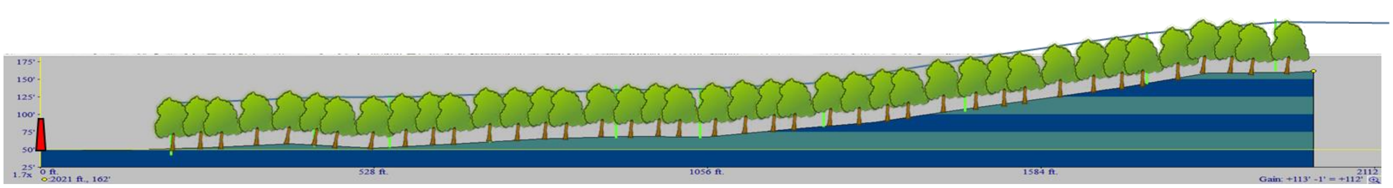


Figure 7 Elevation profile from the compressor station to the nearby hillside as taken along the red line in Fig. 6. Drawing is approximately to scale.

In the descriptions of the computer modeling that I have consulted,[11] nothing is said to indicate that the effects were included of downwash from the nearby hill or from nearby forest. The downwash created by a hill was sketched in Fig. 2c, and is drawn with streamlines in Fig. 8.[12] Figure 9 shows the analogous behavior *computed* for winds flowing over a forest edge and into a clearing, [13] which is exactly the configuration of the proposed compressor station. In Fig. 9, I have denoted with a red marker the stack location and height roughly to scale. Note that the 50-foot stacks would be *lower* than the top of the nearby forest canopy. We see in Fig. 9 that the wind can dive downward into the clearing and pull stack emissions toward the ground. *Figure 9 suggests that the presence of the nearby forest-canopy could influence the local wind pattern at the flue stacks.*

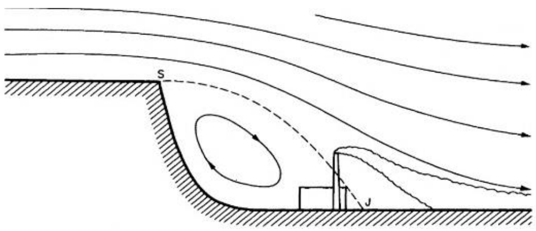


Figure 8 Flow lines showing the downwash that occurs when wind blows over the edge of a hill, and the resultant increase in ground concentrations as the plume is driven down along with the downwash.

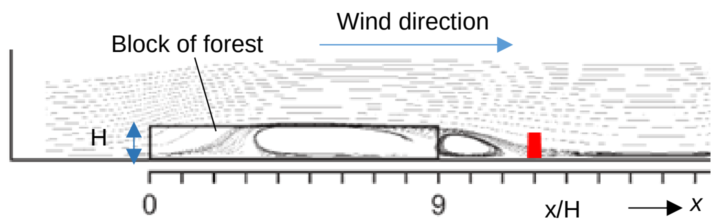


Figure 9 Streamlines showing computed wind pattern flowing over a forest into a clearing. The red flue stack has been added to approximate scale.

Note that Dominion did include the local topology described here in the computer modeling. This topology is used to determine the fate of the plume emitted from the stacks when the plume encounters elements of terrain like the escarpment hillside. However, it is not clear if this modeling would have included the *wind disturbances caused by the hillside or the much closer forest edge*. These disturbances can drive the plume toward the ground and thus increase ground level concentrations.

In the draft Environmental Assessment, FERC dismisses all concerns over the air pollution modeling because the applicant used accepted methods of analysis. However, this analysis is subject to sizable errors as explained above. The risk to local residents is increased if stacks are lowered to accommodate the Mt. Vernon viewshed. At the same time, raising the stacks for improved safety would make the project even more unsuited to the conservation goals of the surrounding area expressed by the Comprehensive Plan, by the federal investment in Piscataway Park, and by the many conservation easements donated by individuals. The conundrum, with possible health issues, underscores just how uniquely unsuitable the site is for such a major industrial facility.

Sincerely,

Jim Long
1135 Overlook Dr
Accokeek MD

[1] That Charles Station is larger than any compressor station in New York state is inferred from testimony for the opposition on October 24, 2017 by Pasquale Russo, Institute for Health and the Environment.

[2]* Course notes available online: http://class.atmos.ucla.edu/AS2/scrns/web%20notes%20(turco%20book)/oldoldpdfs/09disper.big.pdf

[3] *Environmental Engineers Handbook,* David H.F. Liu, Bela G. Liptak CRCnetBASE (1999).

[4] Abbreviated Application For a Certificate of Public Convenience and Necessity, Eastern Market Access Project, Volume I – Public (Nov. 15, 2016) p. 3-4. https://elibrary.ferc.gov/idmws/common/OpenNat.asp?fileID=14398851

[5]* Robynn Andracsek, P.E., Burns & McDonnell and contributing editor of *Power Engineering*. See his article "Just Tall Enough" at http://www.power-eng.com/articles/print/volume-115/issue-6/departments/clearing-the_air/just-tall-enough.html

[6] * *Revision to the Guideline on Air Quality Models: Adoption of a Preferred General Purpose (Flat and Complex Terrain) Dispersion Model and Other Revisions; Final Rule*, Federal Register, Vol. 70, No. 216, November 9, 2005. Environmental Protection Agency 40CFR51. Section 9 discusses the "Accuracy and Uncertainty of Models."

[7] Computed NO_2 is 177.5 $\mu g/m^3$ compared to the allowed value of 188 $\mu g/m^3$. Computed stack emissions are found in Table B.8.1-5, p. 57, of the draft Environmental Assessment.

[8] Dominion's *Abbreviated Application for a Certificate of Public Convenience and Necessity*, *Eastern Market Access Project,* FERC Docket CP17-15. Appendix 9-C, *Supplemental Air Quality Analysis*.

[9] The wind roses were obtained from an online database maintained by the State Climate Office of North Carolina, NC State University, available via this link: https://climate.ncsu.edu/windrose.php?state=VA&station=KDAA

[10] Applicant's Exhibit 12 on BOA Docket for this case.

[11] I have consulted pdfs of the Application for a CPCN (Ref. 4), FERC's Environmental Assessment, and Dominion's application to MDE for an air-quality permit.

[12] Fig. 20 in Air Pollution, R.S. Scorer, Pergamon Press, NY (1968).

[13]* Fig. 6 in *Numerical study of the airflow over forest clearings,* C. Frank and B. Ruck, Forestry **81**, 259 (2008). https://academic.oup.com/forestry/article/81/3/259/659331

**Included as attachment.*

ATTACHMENTS OF DOCUMENTS CITED IN SELECTED ENDNOTES

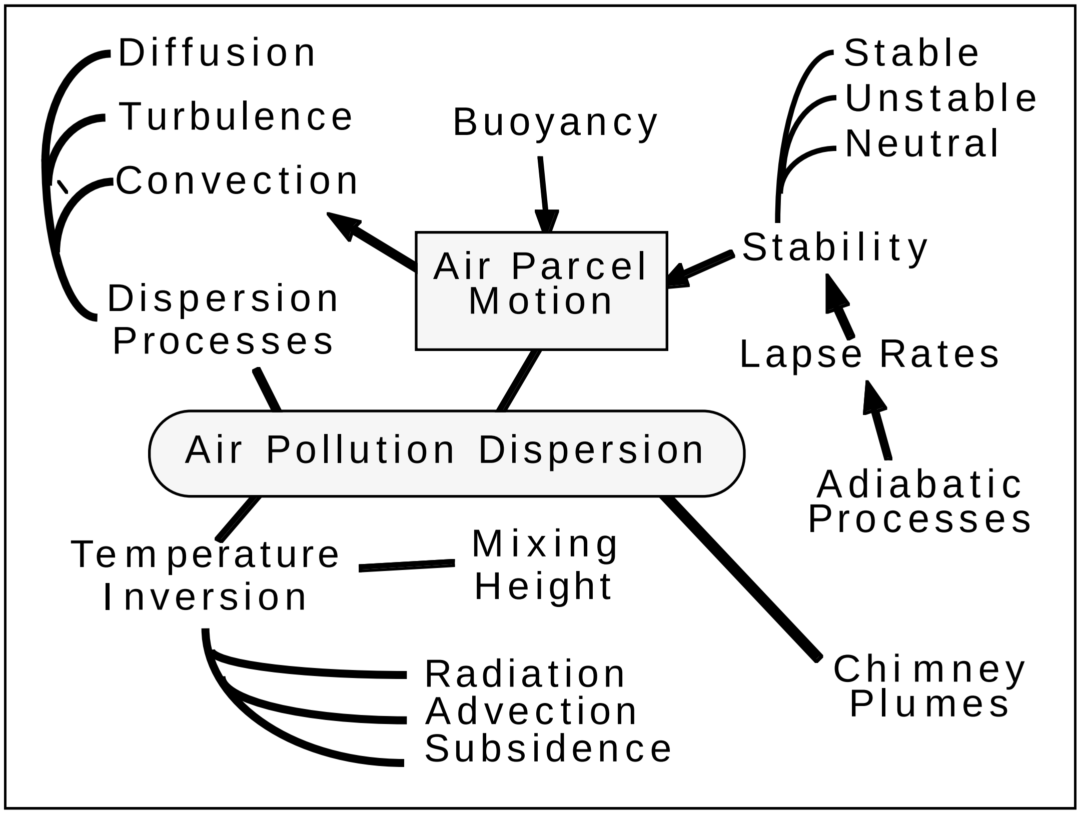
Endnote 2 (source of Fig. 1)

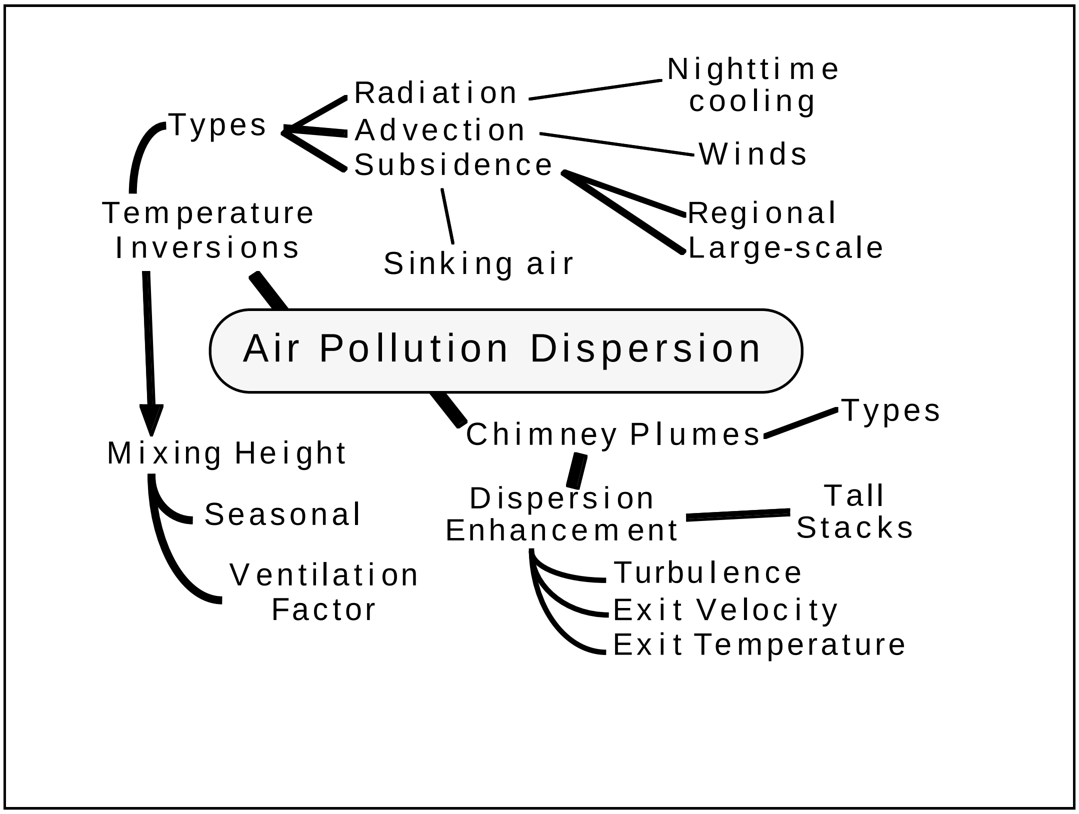
Course notes available online:
http://class.atmos.ucla.edu/AS2/scrns/web%20notes%20(turco%20book)/oldoldpdfs/09disper.big.pdf

Air Pollution Dispersion

- Dispersion Processes
- Convective Dispersion
  - ➔ Air Parcel Dynamics
  - ➔ Adiabatic Process
  - ➔ Lapse Rate
  - ➔ Equilibrium and Stability
  - ➔ Atmospheric Stability
  - ➔ Stability and Dispersion

- Temperature Inversions
  - Stability
  - Formation/Types
  - Mixing Height
- Application: Chimney Plumes
  - Plume Type vs. Stability
  - Enhancing Plume Dispersion


Diffusion
Turbulence
Convection
Dispersion Processes
Buoyancy
Air Parcel Motion
Stable
Unstable
Neutral
Stability
Lapse Rates
Adiabatic Processes
Air Pollution Dispersion
Temperature Inversion
Mixing Height
Radiation
Advection
Subsidence
Chimney Plumes



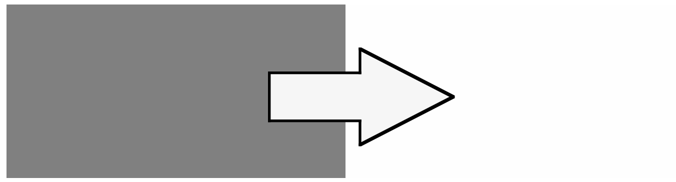
Types
Radiation
Advection
Subsidence
Nighttime cooling
Winds
Regional
Large-scale
Sinking air
Temperature Inversions
Air Pollution Dispersion
Mixing Height
Seasonal
Ventilation Factor
Chimney Plumes
Types
Dispersion Enhancement
Tall Stacks
Turbulence
Exit Velocity
Exit Temperature

Dispersion Processes

Defn.: A substance mixes in and becomes diluted within a larger volume of another substance.

- Molecular Diffusion
- Turbulence
- Convection/Advection

Molecular Diffusion



- Molecules drift from regions of high concentration to regions of lower concentration

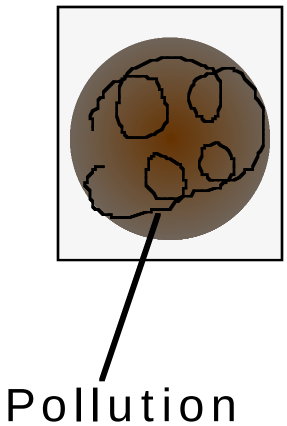
Larger concentration gradient
→ higher diffusion rate

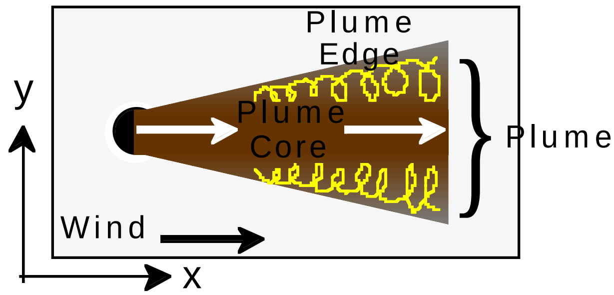
Length scale of motion = molecular

— Slow!!

Turbulence

➪ Bulk air motion in random directions



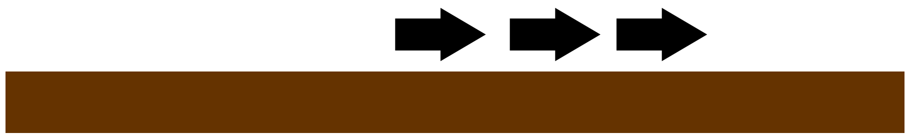


Strong, gusty winds generate the most turbulence

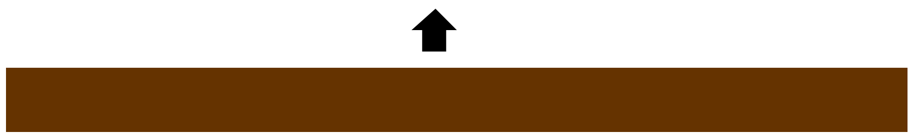
Convection/Advection

Mass transport of pollutants by winds

- Advection: horizontal motion

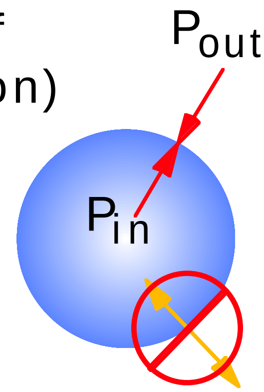


- Convection: vertical motion



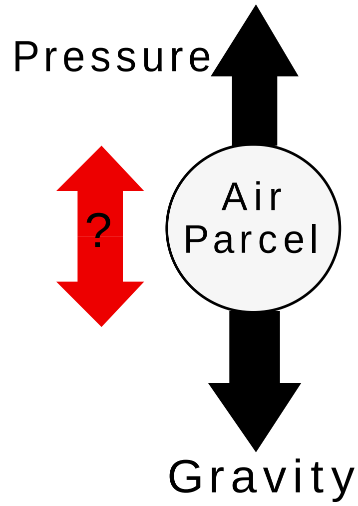
Air Parcel Mechanics

- A specified volume of air (ex.: bubble, balloon)
- Constraints:
  - ➔ P inside = P outside at all times
  - ➔ No mixing of air



Parcel Buoyancy

- Buoyancy: up- or downward force from combination of atmospheric pressure and gravity

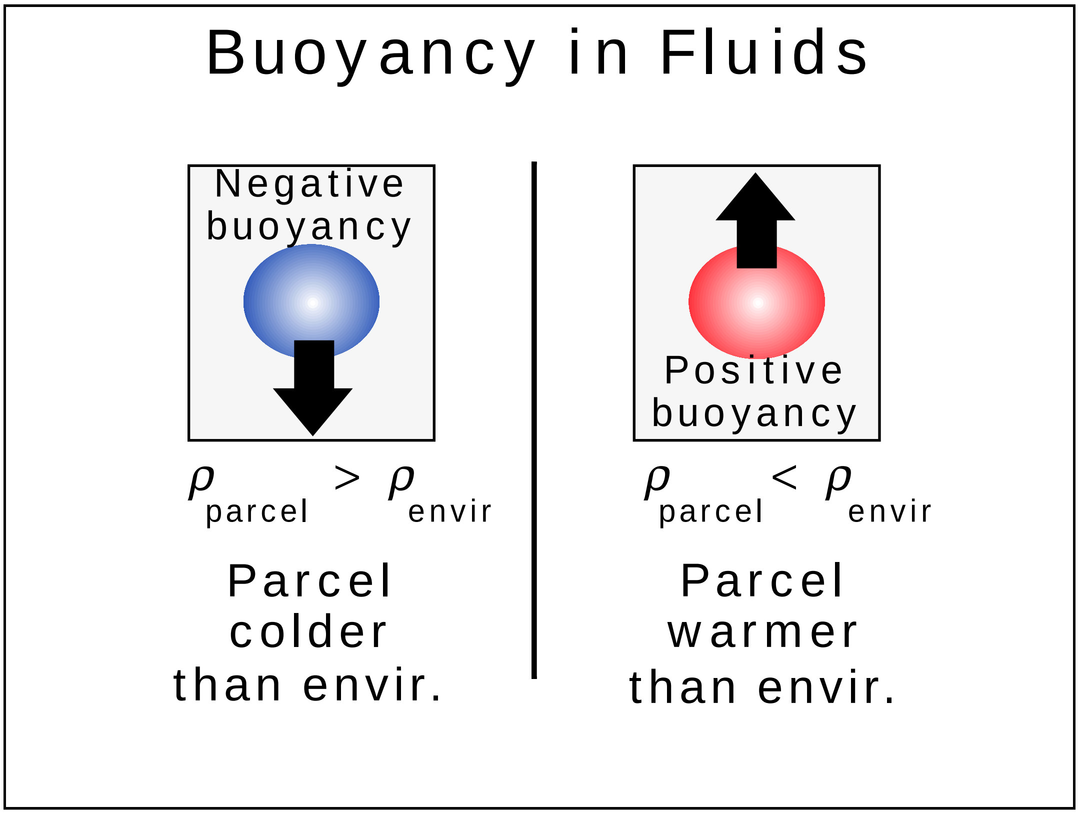


Up- or downward motion of air parcel depends on buoyancy

Air Density vs. Temperature

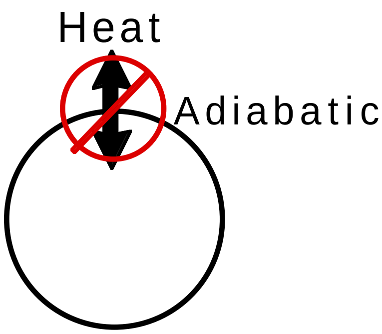
$$\rho \propto \frac{1}{T} \quad \text{for } P = \text{constant}$$

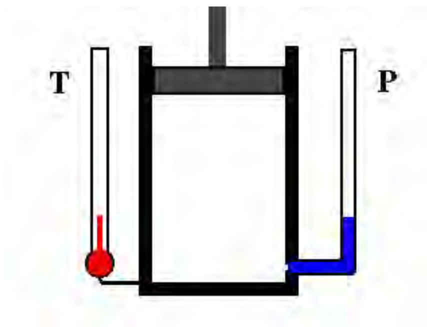
Cold air is more dense than warm air


Buoyancy in Fluids
Negative buoyancy
ρ parcel > ρ envir
Parcel colder than envir.
Positive buoyancy
ρ parcel < ρ envir
Parcel warmer than envir.

Adiabatic Process

➜ No heat exchanged between a system and its surroundings



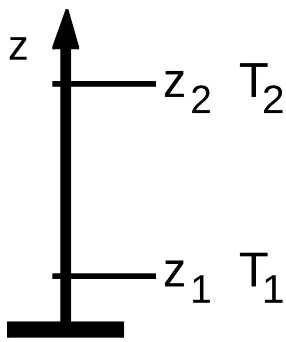


Compression: P ↑, T ↑

Expansion: P ↓, T ↓

Lapse Rate

Defn.: Rate of temperature decrease as altitude increases.



Lapse rate = γ or Γ ("gamma")

$$-\frac{T_2 - T_1}{z_2 - z_1} = -\frac{\Delta T}{\Delta z}$$

$$= \gamma$$

T↓ as z↑ : positive γ

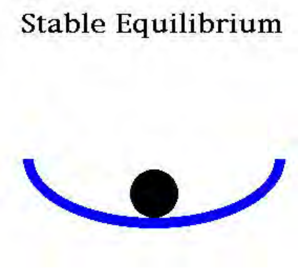
Atmospheric Stability

- Describes behavior of air after it has been disturbed
- Indicates atmosphere's ability to mix vertically
- Related to air parcel buoyancy after perturbing parcel

Stability Behavior

➜ Behavior after disturbance of equilibrium characterizes stability

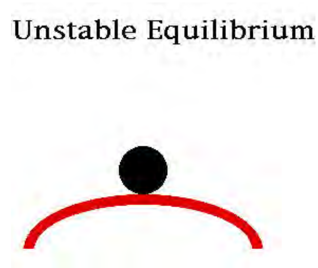
Stable



Stability Behavior

➜ Behavior after disturbance of equilibrium characterizes stability

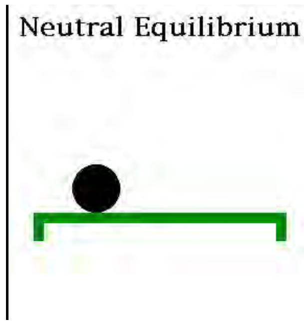
Unstable



Stability Behavior

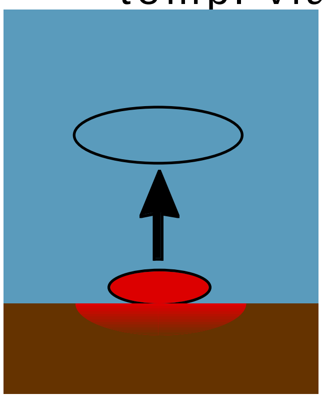
➜ Behavior after disturbance of equilibrium characterizes stability

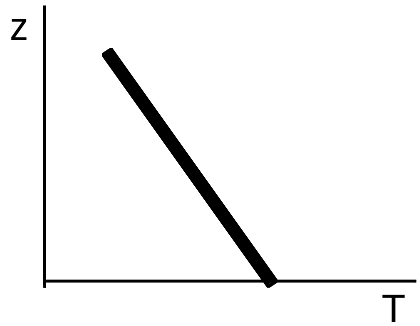
Neutral

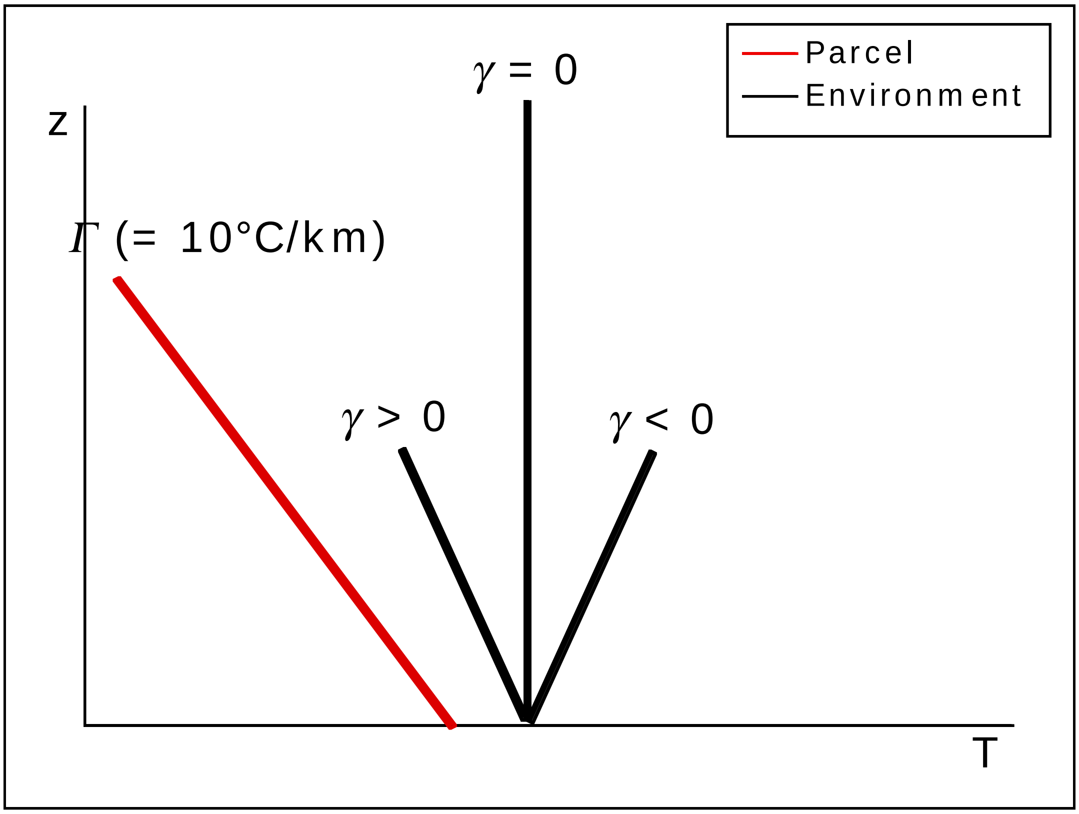


Making Air Parcels Buoyant

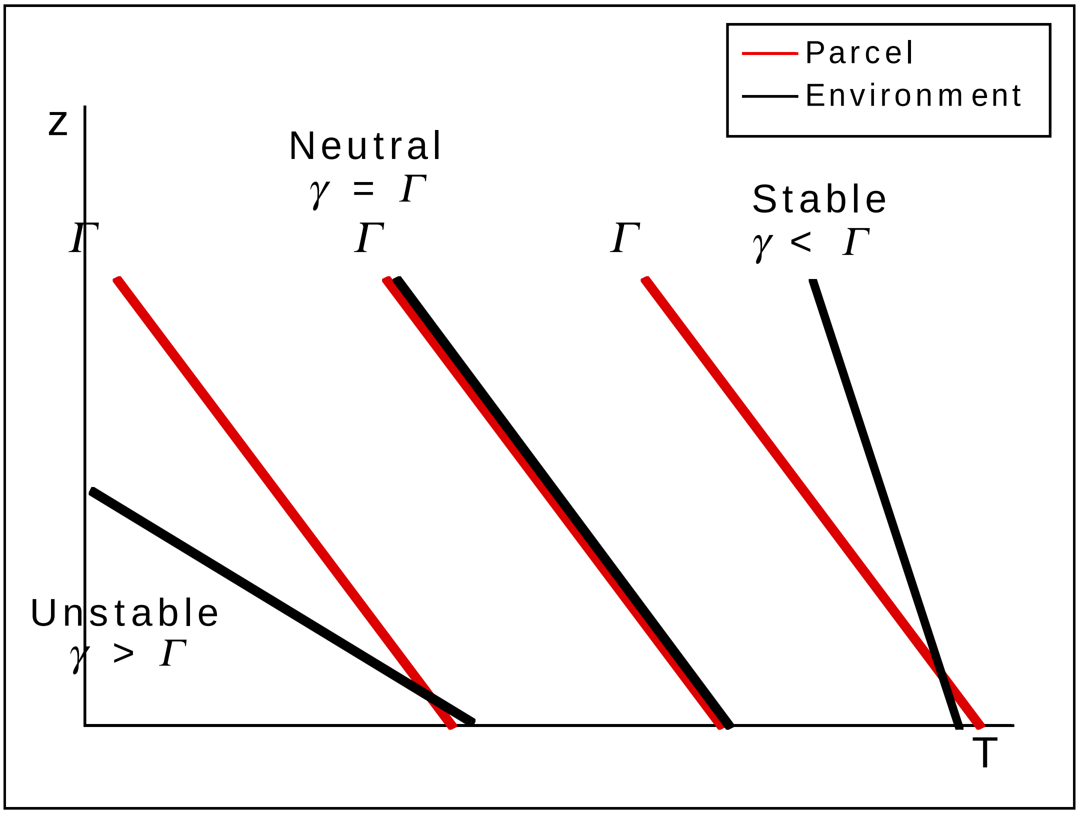
- Need: parcel temp. ≠ envir. temp.
  - ➔ Heat up air parcel at the ground
  - ➔ Or, force parcel upward so it loses temp. via adiabatic expansion







Parcel
Environment
γ = 0
z
Γ (= 10°C/km)
γ > 0
γ < 0
T



Parcel
Environment
z
Neutral
γ = Γ
Γ
Γ
Γ
Stable
γ < Γ
Unstable
γ > Γ
T

Stability Criteria

Stable: $\gamma < \Gamma$

Unstable: $\gamma > \Gamma$

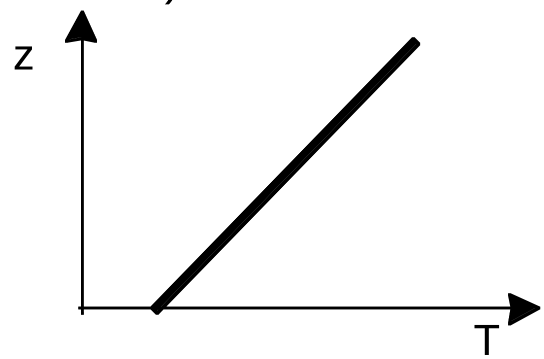
Neutral: $\gamma = \Gamma$

Stability vs. Dispersion

- Turbulence gives parcel initial push
- Stability vs. mixing:
  - Stable—vertical motion suppressed—vertical dispersion discouraged
  - Unstable—vertical motion encouraged—vertical dispersion enhanced

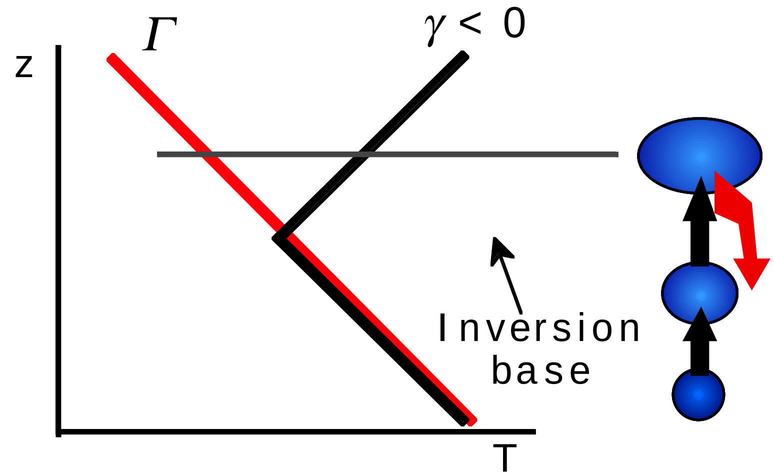
Temperature Inversions

➜ Defn: Temp. increases with increasing altitude ($\gamma < 0$)



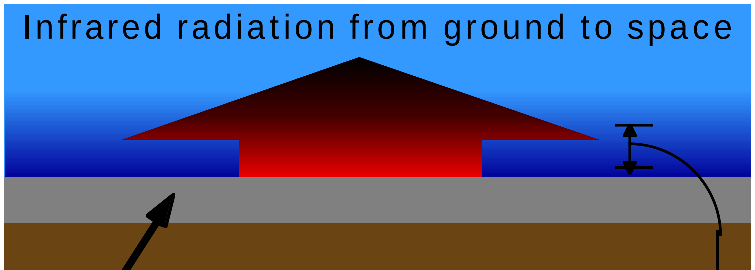
- Inversions are extremely stable

Temperature Inversion Aloft



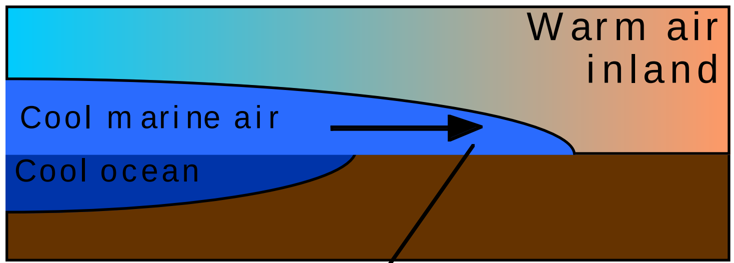
- Radiation Inversion
- Advection Inversion
- Regional Subsidence Inversion
- Large-scale Subsidence Inversion

Radiation Inversion



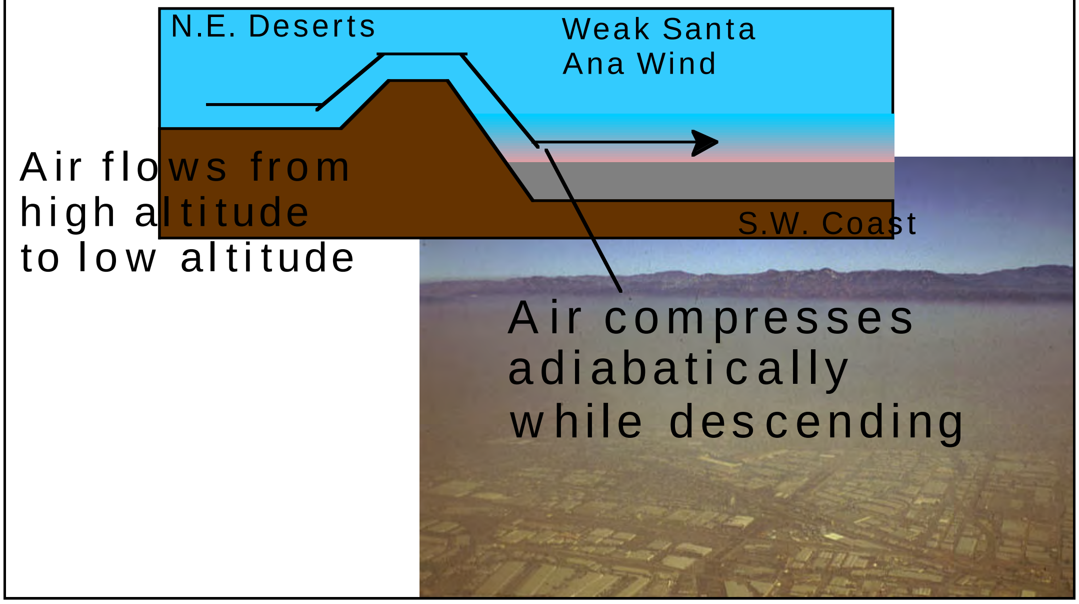
Ground cools off at night; cools air next to it

Advection Inversion

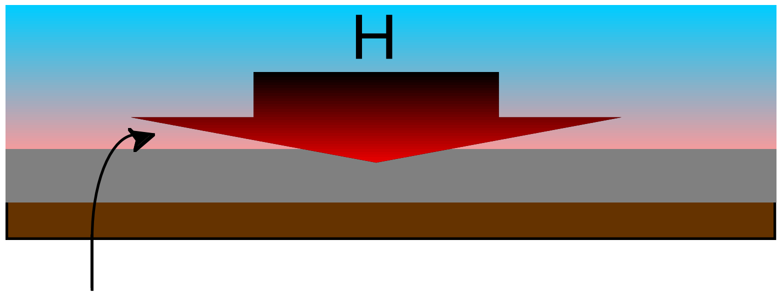


➜ Occurs as Marine Layer along SoCal coast

Regional Subsidence Inversion



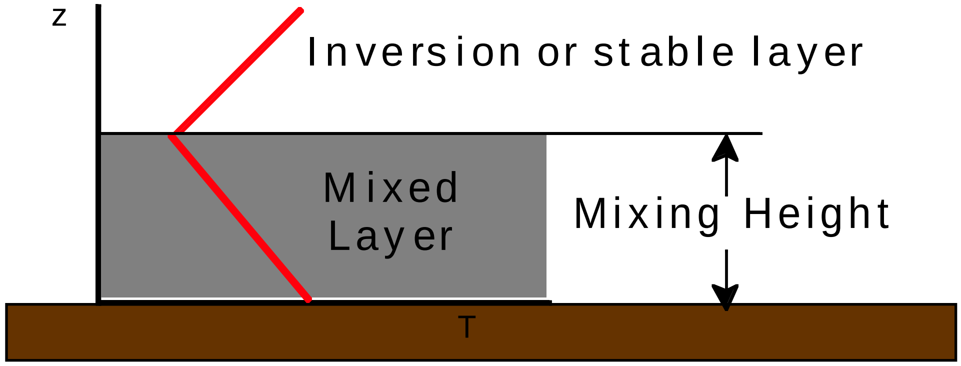
Large-Scale Subsidence Inversion



Air aloft sinks (subsides) and warms from adiabatic compression

➜ L.A. has semi-permanent subsidence inversion

Mixing Heights

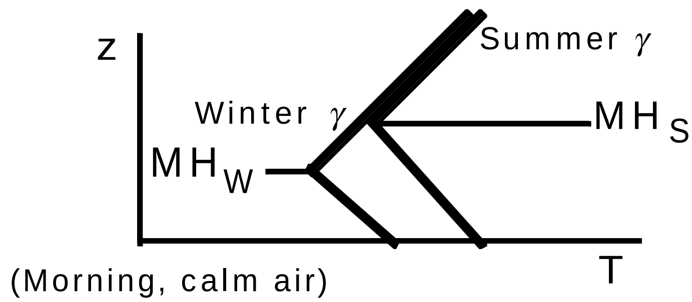


$$\text{Pollution concentration} \propto \frac{1}{\text{Mixing Height}}$$

Mixing Height vs. Season

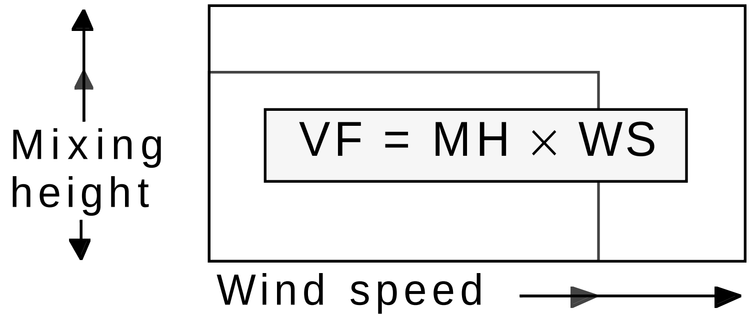
MH ∝ ground temperature

Winter: low temp. | Summer: high temp.

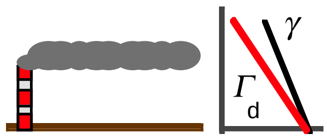


Ventilation Factor

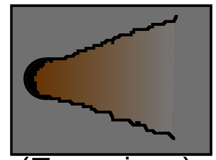
$\propto$ Volume



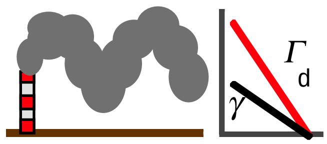
Chimney Plume Dispersion



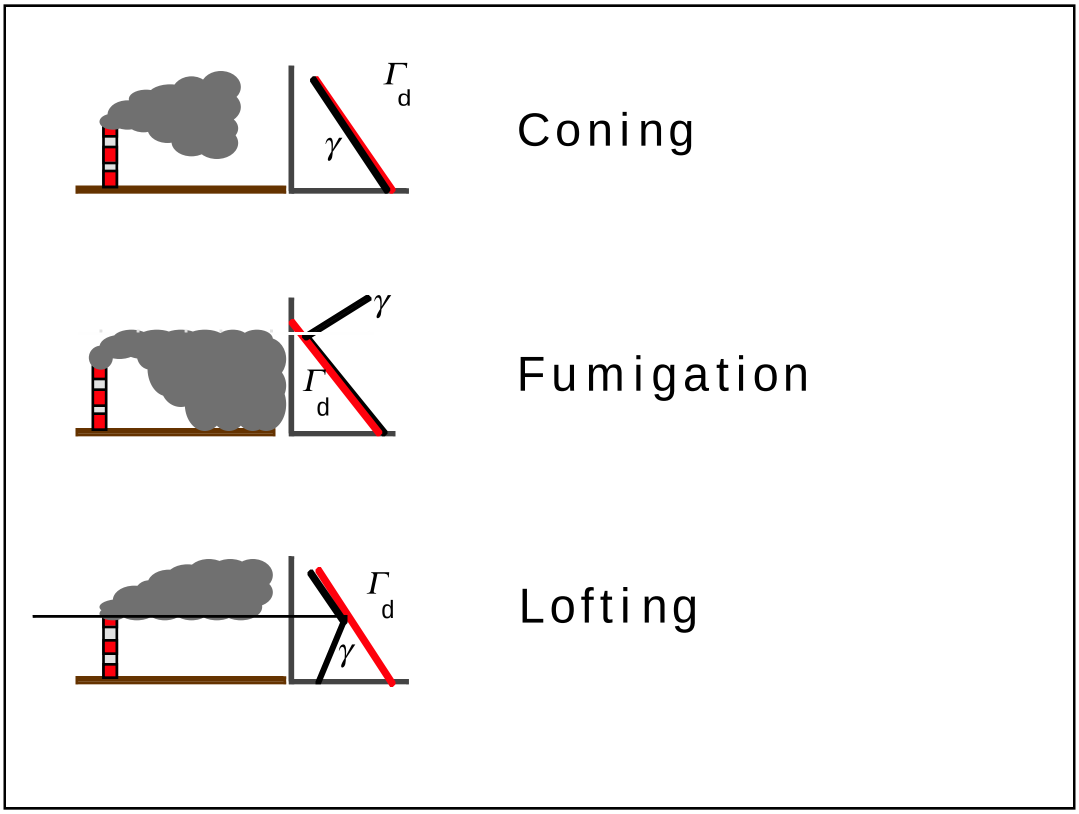
Fanning



(Top view)



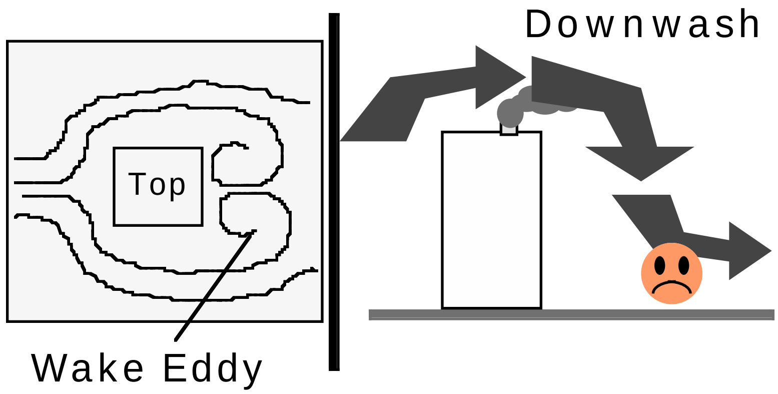
Looping



Γd
γ
Coning
γ
Γd
Fumigation
Γd
γ
Lofting

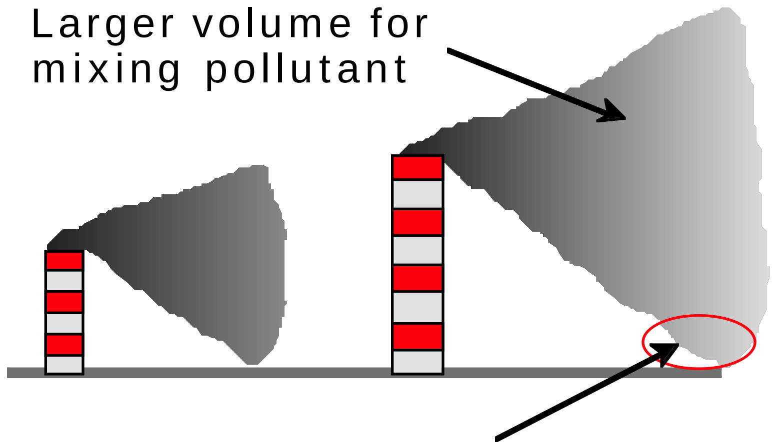
Dispersion Enhancement

Turbulence generated in
flow around buildings

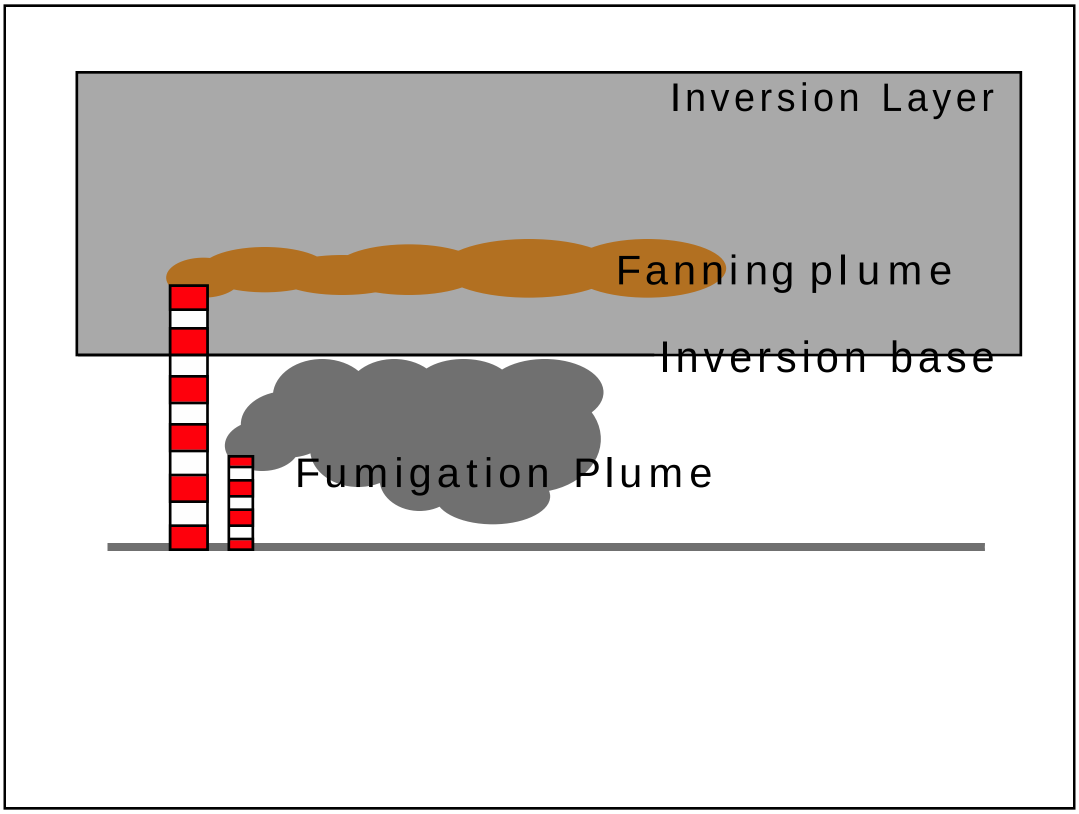


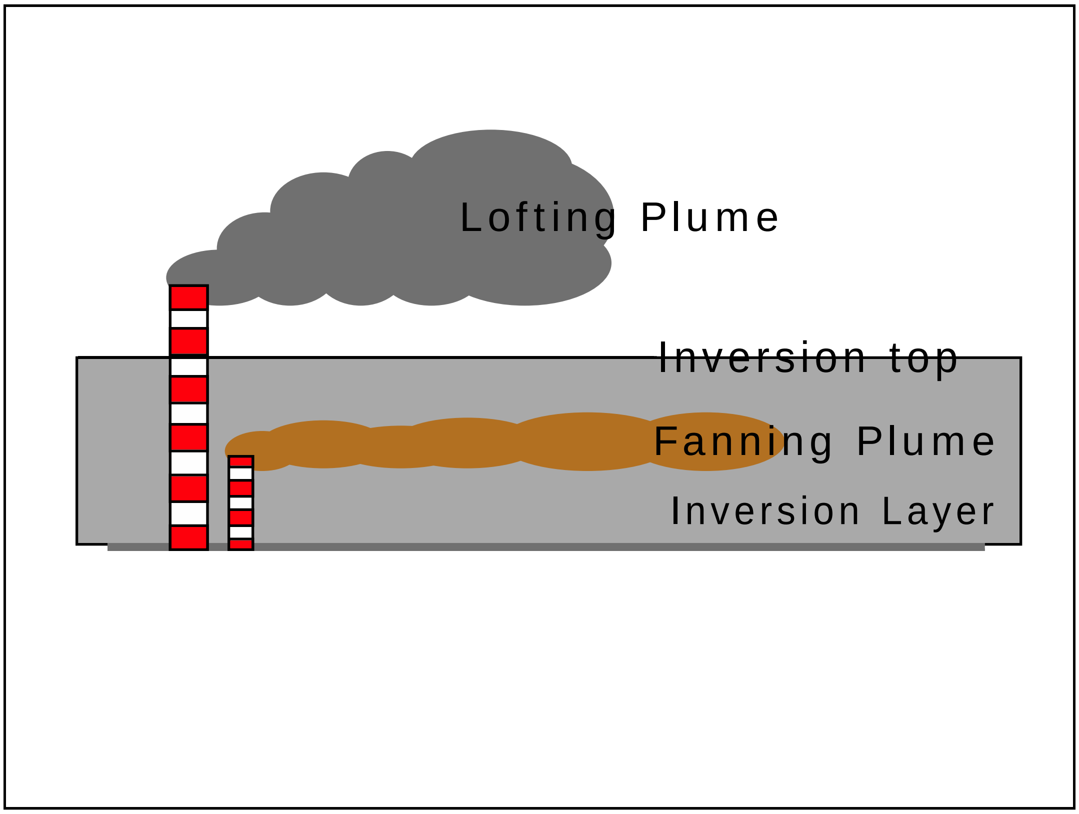
- Tall smokestacks

Larger volume for mixing pollutant

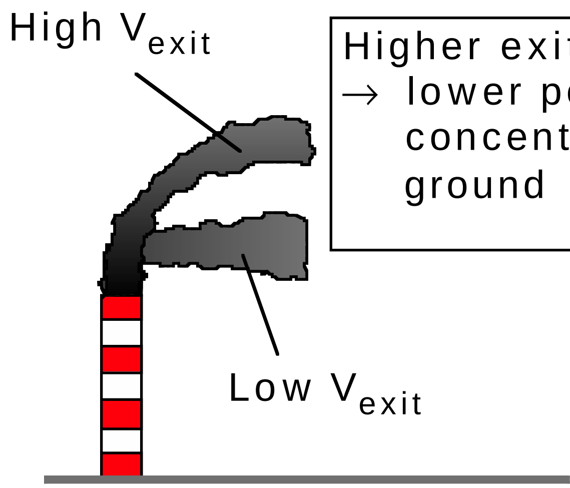


Taller chimney → lower smoke concentration at ground


Inversion Layer
Fanning plume
Inversion base
Fumigation Plume

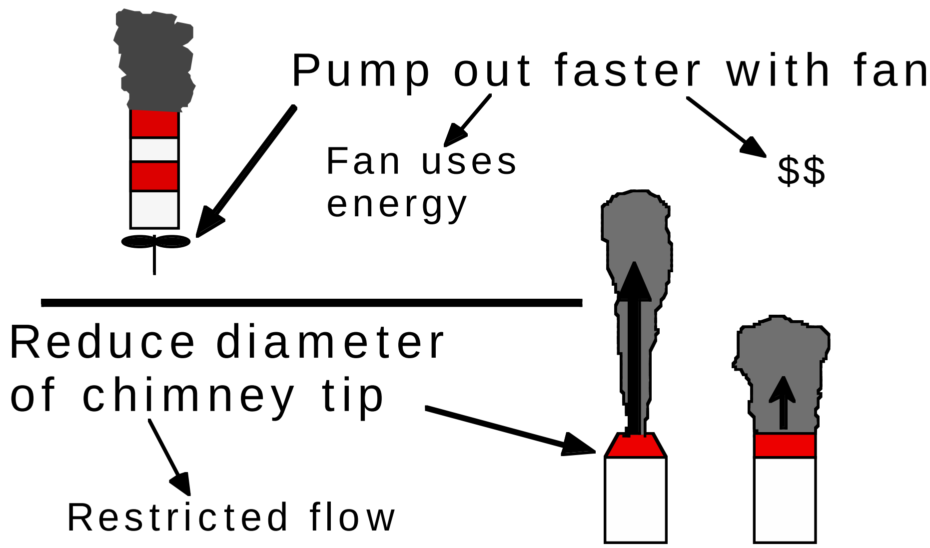

Lofting Plume
Inversion top
Fanning Plume
Inversion Layer

Increase Exit Velocity



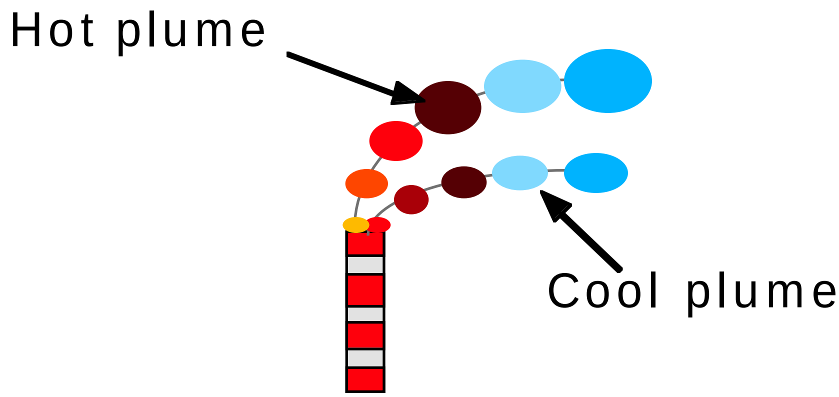
Higher exit velocity
→ lower pollution concentration at ground

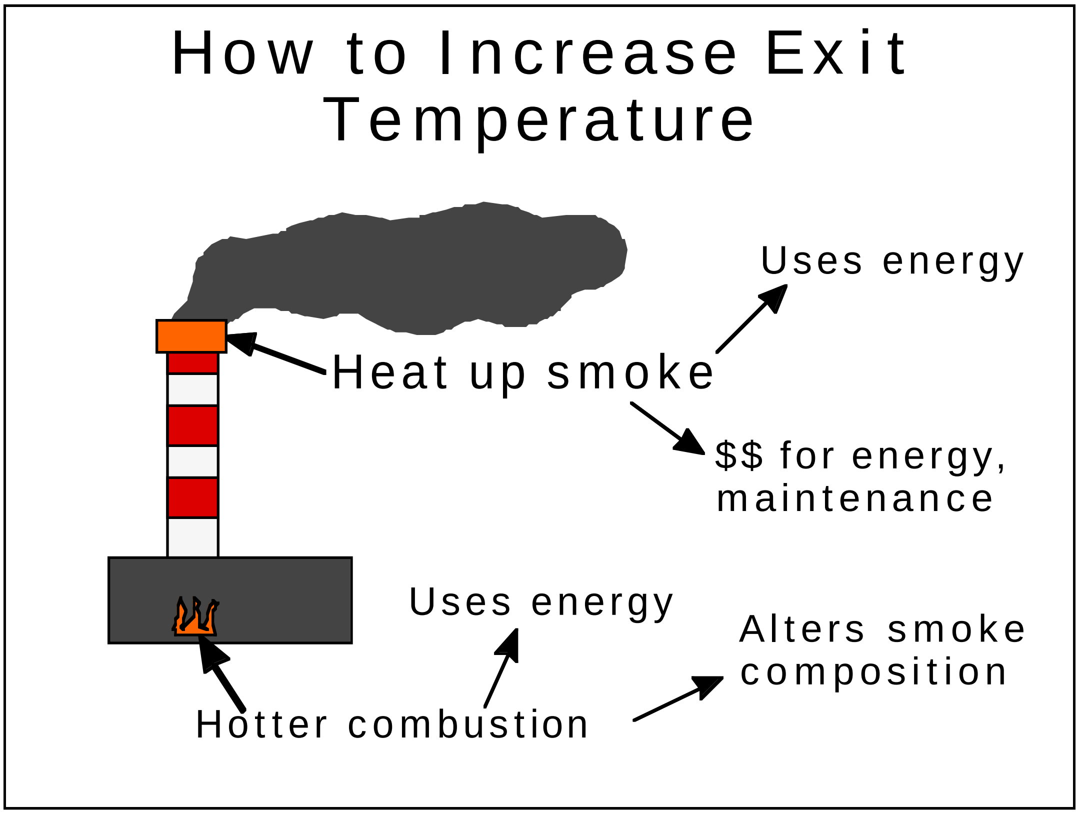
How to Increase Exit Velocity



Increase Exit Temperature

➜ Hotter smoke is more buoyant




How to Increase Exit Temperature
Heat up smoke
Uses energy
$$ for energy, maintenance
Hotter combustion
Uses energy
Alters smoke composition

Endnote 5

Robynn Andracsek, P.E., Burns & McDonnell and contributing editor of *Power Engineering*. See his article "Just Tall Enough" at http://www.power-eng.com/articles/print/volume-115/issue-6/departments/clearing-the_air/justtall-enough.html

POWER Engineering

Just Tall Enough

06/01/2011

By

By Robynn Andracsek, P.E., Burns & McDonnell and Contributing Editor

One question I often am asked is, "How tall should the exhaust stack be?" It's a seemingly simple question, but the only way to get an exact answer is to run an air dispersion model. That takes time, money and a qualified consultant. Not every circumstance allows, or requires, this level of effort. Here is some basic information you may use as a guide.

Air dispersion modeling is required for most Prevention of Significant Deterioration (PSD) permits and some state construction permits. One regulatory requirement is that the modeled concentration, plus the background pollution level, must not exceed the National Ambient Air Quality Standards (NAAQS) or PSD Increment.

Air dispersion modeling using the Environmental Protection Agency's AERMOD algorithm is based on equations with many stack parameters, including stack height, diameter, velocity, temperature and emission rate. Added to this basic description of every stack are its base elevation, where it is located and how it is situated in relation to nearby buildings. Clearly, no single parameter dictates the optimum combination that minimizes ground level pollution concentrations.

As a result, 500 pounds per hour of NO_2 emissions out of a

200-foot-tall stack might have a negligible impact, but 5 pounds per hour of NO_2 emission out of a 20-foot-tall stack with a rain cap could result in concentrations several times the NAAQS or other modeling threshold. Likewise, putting a scrubber on a coal-fired unit does not guarantee 1-hour SO_2 NAAQS compliance since ground level concentrations are directly, but not solely, related to the unit's emission rate.

The first thing to remember when designing a stack for air dispersion modeling compliance is that rain caps often are problematic. Initial dispersion comes from the heat of the exhaust (known as "buoyancy") and how fast it exits the stack ("momentum"). In modeling, a rain cap is considered to be any kind of obstruction on the end of the stack. (The same effect can also be achieved through a horizontal exhaust.) Only a vertical, unobstructed stack is allowed to account for the momentum component of initial dispersion. If rainwater must be prevented from entering the stack, a "tractor flap" type of exhaust will prevent water from entering when the unit is not in operation and allow the exhaust to exit freely when it is.

A common misconception is that good engineering practice (GEP) stack height is a minimum, or recommended, stack height. Not true. GEP dictates not the minimum but the maximum stack height you may take credit for in the model. This prevents constructing mile-high stacks. The solution to pollution is not dilution and most stacks are built to a height shorter than GEP. The GEP stack height is dictated by calculating the stack height in relation to each nearby building's height and crosswind profile. The dominant building is often not even the one on which a stack is located.

GEP stack height is related to what's known as building "downwash." If you've ever been in an alley between two tall buildings on a windy day, you've likely seen leaves swirling around. They are caught in eddies created by wind flowing around the tall structures. The same concept helps explain downwash. The presence of an obstruction changes both the wind's direction and velocity. Every structure will form an aerodynamic wake on its downwind side. The size and intensity of this "downwash zone" will increase in proportion to the wind speed. Stack exhaust discharged into this zone can be pulled down to the ground before it can disperse the way it would in the absence of the building. A rule of thumb is that GEP is 2.5 times the closest, largest building's height, but it is much more complicated. Constructing each stack at GEP height would be an expensive eyesore.

One of the first modeling tools to employ is the ability to restrict a source's operation to certain times of day. Winds are calmer at night and less dispersion occurs. If a source operates from 8 am to 6 pm, consider taking a permit limit if necessary that officially restricts its operations to that time period. You then can eliminate nighttime hours from the dispersion modeling for the particular source. This arrangement would not affect operational flexibility since the facility is already following the limitation and it allows the calmer nighttime hours to be excluded from the model. In terms of shorter averages (other than annual), such a limitation might resolve a modeling exceedance.

Air dispersion modeling is more art than science. As with all art, skill and experience determine the value of the result.

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Endnote 6

Revision to the Guideline on Air Quality Models: Adoption of a Preferred General Purpose (Flat and Complex Terrain) Dispersion Model and Other Revisions; Final Rule, Federal Register, Vol. 70, No. 216, November 9, 2005.
Environmental Protection Agency 40CFR51. Section 9 discusses the "Accuracy and Uncertainty of Models."

Federal Register

Wednesday,
November 9, 2005

Part III

Environmental Protection Agency

40 CFR Part 51

Revision to the Guideline on Air Quality Models: Adoption of a Preferred General Purpose (Flat and Complex Terrain) Dispersion Model and Other Revisions; Final Rule

ENVIRONMENTAL PROTECTION AGENCY

40 CFR Part 51

[AH–FRL–7990–9]

RIN 2060–AK60

Revision to the Guideline on Air Quality Models: Adoption of a Preferred General Purpose (Flat and Complex Terrain) Dispersion Model and Other Revisions

AGENCY: Environmental Protection Agency (EPA).

ACTION: Final rule.

SUMMARY: EPA's *Guideline on Air Quality Models* (''*Guideline*'') addresses the regulatory application of air quality models for assessing criteria pollutants under the Clean Air Act. In today's action we promulgate several additions and changes to the *Guideline.* We recommend a new dispersion model—AERMOD—for adoption in appendix A of the *Guideline.* AERMOD replaces the Industrial Source Complex (ISC3) model, applies to complex terrain, and incorporates a new downwash algorithm—PRIME. We remove an existing model—the Emissions Dispersion Modeling System (EDMS)—from appendix A. We also make various editorial changes to update and reorganize information.

DATES: This rule is effective December 9, 2005. As proposed, beginning November 9, 2006, the new model—AERMOD—*should be* used for appropriate application as replacement for ISC3. During the one-year period following this promulgation, protocols for modeling analyses based on ISC3 which are submitted in a timely manner *may be* approved at the discretion of the appropriate Reviewing Authority. Applicants are therefore encouraged to consult with the Reviewing Authority as soon as possible to assure acceptance during this period.

ADDRESSES: All documents relevant to this rule have been placed in Docket No. A–99–05 at the following address: Air Docket in the EPA Docket Center, (EPA/DC) EPA West (MC 6102T), 1301 Constitution Ave., NW., Washington, DC 20004. This docket is available for public inspection and copying between 8 a.m. and 5:30 p.m., Monday through Friday, at the address above.

FOR FURTHER INFORMATION CONTACT: Tyler J. Fox, Air Quality Modeling Group (MD–D243–01), Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, NC 27711; telephone (919) 541–5562. (*Fox.Tyler@epa.gov*).

SUPPLEMENTARY INFORMATION:

Outline

I. General Information
II. Background
III. Public Hearing on the April 2000 proposal
IV. Discussion of Public Comments and Issues from our April 21, 2000 Proposal
A. AERMOD and PRIME
B. Appropriate for Proposed Use
C. Implementation Issues/Additional Guidance
D. AERMOD revision and reanalyses in 2003
1. Performance analysis for AERMOD (02222)
a. Non-downwash cases: AERMOD (99351) vs. AERMOD (02222)
b. Downwash cases
2. Analysis of regulatory design concentrations for AERMOD (02222)
a. Non-downwash cases
b. Downwash cases
c. Complex terrain
E. Emission and Dispersion Modeling System (EDMS)
V. Discussion of Public Comments and Issues from our September 8, 2003 Notice of Data Availability
VI. Final action
VII. Final editorial changes to appendix W
VIII. Statutory and Executive Order Reviews

I. General Information

A. How Can I Get Copies of Related Information?

EPA established an official public docket for this action under Docket No. A–99–05. The official public docket is the collection of materials that is available for public viewing at the Air Docket in the EPA Docket Center, (EPA/DC) EPA West (MC 6102T), 1301 Constitution Ave., NW., Washington, DC 20004. The EPA Docket Center Public Reading Room (B102) is open from 8:30 a.m. to 4:30 p.m., Monday through Friday, excluding legal holidays. The telephone number for the Reading Room is (202) 566–1744, and the telephone number for the Air Docket is (202) 566–1742. An electronic image of this docket may be accessed via Internet at *www.epa.gov/eDocket,* where Docket No. A–99–05 is indexed as OAR–2003–0201. Materials related to our Notice of Data Availability (published September 8, 2003) and public comments received pursuant to the notice were placed in eDocket OAR–2003–0201.[1]

Our Air Quality Modeling Group maintain an Internet website (Support Center for Regulatory Air Models—SCRAM) at: *www.epa.gov/scram001.* You may find codes and documentation for models referenced in today's action on the SCRAM Web site. We have also uploaded various support documents (*e.g.,* evaluation reports).

II. Background

The *Guideline* is used by EPA, States, and industry to prepare and review new source permits and State Implementation Plan revisions. The *Guideline* is intended to ensure consistent air quality analyses for activities regulated at 40 CFR 51.112, 51.117, 51.150, 51.160, 51.166, and 52.21. We originally published the *Guideline* in April 1978 and it was incorporated by reference in the regulations for the Prevention of Significant Deterioration (PSD) of Air Quality in June 1978. We revised the *Guideline* in 1986, and updated it with supplement A in 1987, supplement B in July 1993, and supplement C in August 1995. We published the *Guideline* as appendix W to 40 CFR part 51 when we issued supplement B. We republished the *Guideline* in August 1996 (61 FR 41838) to adopt the CFR system for labeling paragraphs. On April 21, 2000 we issued a Notice of Proposed Rulemaking (NPR) in the **Federal Register** (65 FR 21506), which was the original proposal for today's promulgation.

III. Public Hearing on the April 2000 Proposal

We held the 7th Conference on Air Quality Modeling (7th conference) in Washington, DC on June 28–29, 2000. As required by Section 320 of the Clean Air Act, these conferences take place approximately every three years to standardize modeling procedures, with special attention given to appropriate modeling practices for carrying out programs PSD (42 U.S.C. 7620). This conference served as the forum for receiving public comments on the *Guideline* revisions proposed in April 2000. The 7th conference featured presentations in several key modeling areas that support the revisions promulgated today. A presentation by the American Meteorological Society (AMS)/EPA Regulatory Model Improvement Committee (AERMIC) covered the enhanced Gaussian dispersion model with boundary layer parameterization: AERMOD.[2] Also at the 7th conference, the Electric Power Research Institute (EPRI) presented evaluation results from the recent research efforts to better define and characterize dispersion around

[1] *http://cascade.epa.gov/RightSite/dk_public_collection_detail.htm?ObjectType=dk_docket_collection&cid=OAR-2003-0201&ShowList=items&Action=view.*

[2] *AMS/EPA Regulatory MODel.*

buildings (downwash effects). These efforts were part of a program called the Plume RIse Model Enhancements (PRIME). At the time, PRIME was integrated within ISC3ST (*ISC–PRIME*) and the results presented were within the ISC3 context. As discussed in today's rule, the PRIME algorithm has now been fully integrated into AERMOD.

We proposed an update to the Emissions and Dispersion Modeling System (EDMS 3.1), which is used for assessing air quality impacts from airports. A representative of the Federal Aviation Administration (FAA) presented a further upgrade to EDMS 4.0 that would include AERMOD and forthcoming performance evaluations for two airports.

The presentations were followed by a critical review/discussion of AERMOD and available performance evaluations, facilitated jointly by the Air & Waste Management Association's AB–3 Committee and the American Meteorological Society's Committee of Meteorological Aspects of Air Pollution.

For the new models and modeling techniques proposed in April 2000, we asked the public to address the following questions:

- Has the scientific merit of the models presented been established?
- Are the models' accuracy sufficiently documented?
- Are the proposed regulatory uses of individual models for specific applications appropriate and reasonable?
- Do significant implementation issues remain or is additional guidance needed?
- Are there serious resource constraints imposed by modeling systems presented?
- What additional analyses or information are needed?

We placed a transcript of the 7th conference proceedings and a copy of all written comments, many of which address the above questions, in Docket No. A–99–05. The comments on AERMOD were reviewed and nearly every commenter urged us to integrate aerodynamic downwash into AERMOD (i.e., not to require two models for some analyses). The only comments calling for further actions were associated with the need for documentation, evaluation and review of the suggested downwash enhancement to AERMOD.

As a result of American Meteorological Society (AMS)/EPA Regulatory Model Improvement Committee's (AERMIC) efforts to revise AERMOD, incorporating the PRIME algorithm and making certain other incidental modifications and to respond to public concerns, we believed that the revised AERMOD merited another public examination of performance results. Also, since the April 2000 NPR, the Federal Aviation Administration (FAA) decided to configure EDMS 3.1 to incorporate the AERMOD dispersion model. FAA presented this strategy at the 7th conference and performance evaluations at two airports were to be available before final promulgation. This was in response to public concern over lack of EDMS evaluation.

On April 15, 2003 we published a Notice of Final Rulemaking (NFR; 68 FR 18440) that adopted CALPUFF in appendix A of the *Guideline.* We also made various editorial changes to update and reorganize information, and removed obsolete models. We announced that action on AERMOD and the Emissions and Dispersion Model (EDMS) for assessing airport impacts was being deferred, and would be reconsidered in a separate action when new information became available for these models.

This deferred action took the form of a Notice of Data Availability (NDA), which was published on September 8, 2003 (68 FR 52934). In this notice, we made clear that the purpose of the NDA was to furnish pertinent technical details related to model changes since the April 2000 NPR. New performance data and evaluation of design concentration using the revised AERMOD are contained in reports cited later in this *preamble* (see section V). In our April 2003 NFR, we stated that results of EDMS 4.0 performance (with AERMOD) had recently become available. In the NDA we clarified that these results would not be provided because of FAA's decision to withdraw EDMS from the *Guideline's* appendix A, and we affirmed our support for this removal. We solicited public comments on the new data and information related to AERMOD.

IV. Discussion of Public Comments and Issues From Our April 21, 2000 Proposal

All comments submitted to Docket No. A–99–05 are filed in Category IV–D.[3] We summarized these comments, developed detailed responses, and documented conclusions on appropriate actions in a Response-to-Comments document.[4] In this document, we considered and discussed all significant comments. Whenever the comments revealed any new information or suggested any alternative solutions, we considered this prior to taking final action.

The remainder of this preamble section discusses the primary issues encountered by the Agency during the public comment period associated with the April 2000 proposal. This overview also serves in part to explain the changes to the *Guideline* in today's action, and the main technical and policy concerns addressed by the Agency.

A. AERMOD and PRIME

AERMOD is a best state-of-the-practice Gaussian plume dispersion model whose formulation is based on planetary boundary layer principles. AERMOD provides better characterization of plume dispersion than does ISC3. At the 7th conference, AERMIC members presented developmental and evaluation results of AERMOD. Comprehensive comments were submitted on the AERMOD code and formulation document and on the AERMET draft User's Guide (AERMET is the meteorological preprocessor for AERMOD).

As identified in the April 2000 **Federal Register** proposal, applications for which AERMOD was suited include assessment of plume impacts from stationary sources in simple, intermediate, and complex terrain, for *other than* downwash and deposition applications. We invited comments on whether technical concerns had been reasonably addressed and whether AERMOD is appropriate for its intended applications. Since AERMOD lacks a general (all-terrain) screening tool, we invited comment on the practicality of using SCREEN3 as an interim tool for AERMOD. We also sought comments on minor changes to the list of acceptable screening techniques for complex terrain.

PRIME was designed to incorporate the latest scientific algorithms for evaluating building downwash. At the time of the proposal, the PRIME algorithm for simulating aerodynamic downwash was not incorporated into AERMOD. For testing purposes, PRIME was implemented within ISC3ST (short-term average version of the Industrial Source Complex), which AERMOD was proposed to replace. This special model, called *ISC–PRIME,* was proposed for

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[3] Additional comments received since we published the final rule on April 15, 2003 (discussed in the previous section) are filed in category IV–E. This category includes comments received pursuant to the Notice of Data Availability we published in September 2003.

[4] Summary of Public Comments and EPA Responses: AERMOD; 7th Conference on Air Quality Modeling; Washington, DC, June 28–29, 2000 AND Notice of Data Availability—September 8, 2003 (Air Docket A–99–05, Item V–C–2). This document may also be examined from EPA's SCRAM Web site at *www.epa.gov/scram001.*

aerodynamic downwash and dry deposition. We sought comment on the technical viability of AERMOD and ISC–PRIME for its intended applications.

Scientific merit and accuracy. Regarding the scientific merits of AERMOD, substantial support was expressed in public comments that AERMOD represents sound and significant advances over ISC3ST. The scientific merits of this approach have been documented both through scientific peer review and performance evaluations. The formulation of AERMOD has been subjected to an extensive, independent peer review.[5] Findings of the peer review panel suggest that AERMOD's scientific basis is ''state-of-the-science.'' Additionally, the model formulations used in AERMOD and the performance evaluations have been accepted for publication in two refereed journals.[6 7] Finally, the adequacy of AERMOD's complex terrain approach for regulatory applications is seen most directly in its performance. AERMOD's complex terrain component has been evaluated extensively by comparing model-estimated regulatory design values and concentration frequency distributions with observations. These comparisons have demonstrated AERMOD's superiority to ISC3ST and CTDMPLUS (Complex Terrain Dispersion Model PLUS unstable algorithms) in estimating those flat and complex terrain impacts of greatest regulatory importance.[8] For incidental and unique situations involving a well-defined hill or ridge and where a detailed dispersion analysis of the spatial pattern of plume impacts is of interest, CTDMPLUS in the *Guideline*'s appendix A remains available.

Public comments also supported our conclusion about the scientific merits of PRIME. A detailed article in a peer-reviewed journal has been published which contains all the basic equations with clear definitions of the variables, and the reasoning and references for the model assumptions.[9]

Although some comments asked for more detailed documentation and review, there were no comments which questioned the technical credibility of the PRIME model. In fact, almost every commenter asked for PRIME to be incorporated into AERMOD. As summarized above, we believe that the scientific merit of PRIME has been established via (1) model evaluation and documentation, (2) peer review within the submittal process to a technical journal, and (3) via the public review process.

Based on the external peer review of the evaluation report and the public review comments, we have concluded that: (1) AERMOD's accuracy is adequately documented; (2) AERMOD's accuracy is an improvement over ISC3ST's ability to predict measured concentrations; and (3) AERMOD is an acceptable regulatory air dispersion model replacement for ISC3ST.

Some commenters have identified what they perceived to be weaknesses in the evaluation and performance of ISC–PRIME,[10] and some concerns were raised about the scope of the PRIME evaluation. However, as shown by the overwhelming number of requests for the incorporation of PRIME into AERMOD, commenters were convinced that the accuracy of PRIME, as implemented within the ISC3ST framework, was reasonably documented and found acceptable for regulatory applications. Although some commenters requested more evaluations, practical limitations on the number of valid, available data sets prevented the inclusion of every source type and setting in the evaluation. All the data bases that were reasonably available were used in the development and evaluation of the model, and those data bases were sufficient to establish the basis for the evaluation. Based on our review of the documentation and the public comments, we conclude that the accuracy of PRIME is sufficiently documented and find it acceptable for use in a dispersion model recommended in the *Guideline.*

B. Appropriate for Proposed Use

Responding to a question posed in our April 2000 proposal, the majority of commenters questioned the reasonableness of requiring simultaneous use of two models (ISC–PRIME and AERMOD) for those sources with potential downwash concerns. Commenters urged the Agency to eliminate the need to use two models for evaluating the same source. In response to this request, AERMIC developed a version of AERMOD that incorporates PRIME: AERMOD (02222) and initiated an analysis to insure that concentration estimates by AERMOD (02222) are equivalent to ISC–PRIME predictions in areas affected by downwash before it replaces ISC–PRIME. Careful thought was given to the way that PRIME was incorporated into AERMOD, with the goal of making the merge seamless. While discontinuities from the concatenation of these two sets of algorithms were of concern, we mitigated this situation wherever possible (see part D of this preamble, and the Response to Comments document[4]). With regard to testing the performance of AERMOD (02222), we have carefully confirmed that the AERMOD (02222)'s air quality concentration predictions in the wake region reasonably compare to those predictions from ISC–PRIME. In fact, the results indicate that AERMOD (02222)'s performance matches the performance of ISC–PRIME, and are presented in an updated evaluation report[11] and analysis of regulatory design concentrations.[12] We discuss AERMOD (02222) performance in detail in part D.

Because the technical basis for the PRIME algorithms and the AERMOD formulations have been independently peer-reviewed, we believe that further peer review of the new model (AERMOD 02222) is not necessary. The scientific formulation of the PRIME algorithms has not been changed. However, the coding for the interface between PRIME and the accompanying dispersion model had to be modified somewhat to accommodate the different ways that ISC3ST and AERMOD simulate the atmosphere. The main public concern was the interaction between the two models and whether the behavior would be appropriate for all reasonable source settings. This concern was addressed through the extensive testing conducted within the performance evaluation[11] and analysis of design concentrations.[12] Both sets of

[5] U.S. Environmental Protection Agency, 2002. Compendium of Reports from the Peer Review Process for AERMOD. February 2002. Available at *www.epa.gov/scram001/.*

[6] Cimorelli, A. *et al.,* 2005. AERMOD: A Dispersion Model for Industrial Source Applications. Part I: General Model Formulation and Boundary Layer Characterization. *Journal of Applied Meteorology,* 44(5): 682–693.

[7] Perry, S. *et al.,* 2005. AERMOD: A Dispersion Model for Industrial Source Applications. Part II: Model Performance against 17 Field Study Databases. *Journal of Applied Meteorology,* 44(5): 694–708.

[8] Paine R. J. *et al.,* 1998. Evaluation Results for AERMOD, Draft Report. Docket No. A–99–05; II–A–05. Available at *www.epa.gov./scram001/.*

[9] Schulman, L.L. *et al.,* 2000. Development and Evaluation of the PRIME Plum Rise and Building Downwash Model. JAWMA 50: 378–390.

[10] Electric Power Research Institute, 1997. Results of the Independent Evaluation of ISCST3 and ISC–PRIME. Final Report, TR–2460026, November 1997. Available at *www.epa.gov/scram001/.*

[11] Environmental Protection Agency, 2003. AERMOD: Latest Features and Evaluation Results. Publication No. EPA–454/R–03–003. Available at *www.epa.gov/scram001/.*

[12] Environmental Protection Agency, 2003. Comparison of Regulatory Design Concentrations: AERMOD versus ISC3ST, CTDMPLUS, and ISC–PRIME. Final Report. Publication No. EPA–454/R–03–002. Available at *www.epa.gov/scram001/.*

analyses indicate that the new model is performing acceptably well and the results are similar to those obtained from the earlier performance evaluation [8] [10] and analysis of regulatory design concentrations (*i.e.*, for AERMOD (99351)).[13]

While dry deposition is treated in ISC3ST, time and resources did not allow its incorporation in AERMOD (99351). Since no recommendation for deposition is made for regulatory applications, we did not consider that the absence of this capability compromises the suitability of AERMOD for its intended purposes. Nevertheless, a number of commenters requested that deposition algorithms be added to AERMOD, and we developed an update to AERMOD (02222) that offers dry and wet deposition for both gases and particles as an option.

The version of AERMOD under review at the 7th Conference was AERMOD (99351) and, as mentioned above, AERMIC has made a number of changes to AERMOD (99351) following this conference. These changes were initiated in response to public comments and, after the release of a new draft version of the model, in response to the recommendations from the *beta* testers. Changes made to AERMOD include the following:

- Adding the PRIME algorithms to the model (response to public comments);
- Modifying the complex terrain algorithms to make AERMOD less sensitive to the selection of the domain of the study area (response to public comments);
- Modifying the urban dispersion for low-level emission sources, such as area sources, to produce a more realistic urban dispersion and, as a part of this change, changing the minimum layer depth used to calculate the effective dispersion parameters for all dispersion settings (scientific formulation correction which was requested by beta testers); and
- Upgrading AERMOD to include all the newest features that exist in the latest version of ISC3ST such as Fortran90 compliance and allocatable arrays, EVENTS processing and the TOXICS option (response to public comments).

In the follow-up quality control checking of the model and the source code, additional changes were identified as necessary and the following revisions were made:

- Adding meander treatment to: (1) Stable and unstable urban cases, and (2) the rural unstable dispersion settings (only the rural, stable dispersion setting considered meander in AERMOD (99351)—this change created a consistent treatment of air dispersion in all dispersion settings);
- Making some changes to the basic meander algorithms (improved scientific formulation); and
- Repairing miscellaneous coding errors.

As we mentioned earlier, the version of AERMOD that is being promulgated today—AERMOD (02222)—has been subjected to further performance evaluation [11] and analysis of design concentrations.[12]

C. Implementation Issues/Additional Guidance

Other than miscellaneous suggestions for certain enhancements for AERMOD (99351) such as a Fortran90 compilation of the source code, creation of allocatable arrays, and development of a Windows® graphical user interface, no significant implementation obstacles were identified in public comments.

For AERMET (meteorological preprocessor for AERMOD), we have implemented some enhancements that commenters suggested. For site-specific applications, several commenters cited AERMOD's requirements for NWS cloud cover data. In response, we revised the AERMET to incorporate the bulk Richardson number methodology. This approach uses temperature differences near the surface of the earth, which can be routinely monitored, and eliminates the need for the cloud cover data at night. We made a number of other revisions in response to public comments, enabling AERMET to: (1) Use the old and the new Forecasting Systems Laboratory formats, (2) use the Hourly U.S. Weather Observations/Automated Surface Observing Stations (HUSWO/ASOS) data, (3) use site-specific solar radiation and temperature gradient data to eliminate the need for cloud cover data, (4) appropriately handle meteorological data from above the arctic circle, and (5) accept a wider range of reasonable friction velocities and reduce the number of warning messages. As mentioned earlier, we added a meander component to the treatment of stable and unstable urban conditions to consistently treat meander phenomena for all cases.

AERMAP (the terrain preprocessor for AERMOD) has been upgraded in response to public comments calling for it to: (1) Treat complex terrain receptors without a dependance on the selected domain, (2) accommodate the Spatial Data Transfer Standard (SDTS) data available from the U.S. Geological Survey (USGS), (3) appropriately use Digital Elevation Model (DEM) data with 2 different datums (NAD27 and NAD83); (4) accept all 7 digits of the North UTM coordinate, and (5) do more error-checking in the raw data (mostly checking for missing values, but not for harsh terrain changes in adjacent points). All of these recommendations have been implemented.

In response to comments about the selection of the domain affecting the results of the maximum concentrations in complex terrain and the way AERMAP estimates the effective hill height scale (h_C), the algorithms within AERMAP and AERMOD have been adjusted so that the hill height is less sensitive to the arbitrary selection of the domain. This adjustment has been evaluated against the entire set of evaluation data. The correction was found to substantially reduce the effect of the domain size upon the computation of controlling hill heights for each receptor. Application of this change to the evaluation databases did not materially affect the evaluation results.

In general, public comments that requested additional guidance were either obviated by revisions to AERMOD (99351) and its related preprocessors or deemed unnecessary. In the latter case, the reasons were explained in the Response-to-Comments document.[4]

Some public comments suggested additional testing of AERMOD (99351). In fact, after the model revisions that were described earlier were completed, AERMOD (02222) was subjected to additional testing.[11] [12] These new analyses will be discussed in part D.

With respect to a screening version of AERMOD, a tool called AERSCREEN is being developed with a beta version expected to be publicly available in Fall 2005. SCREEN3 is the current screening model in the *Guideline,* and since SCREEN3 has been successfully applied for a number of years, we believe that SCREEN3 produces an acceptable degree of conservatism for regulatory applications and may be used until AERSCREEN or a similar technique becomes available and tested for general application.

D. AERMOD Revision and Reanalyses Published In 2003

1. Performance Analysis for AERMOD (02222)

We have tested the performance of AERMOD (02222) by applying all of the original data sets used to support the version proposed in April, 2000: AERMOD (99351) [8] and ISC–PRIME.[10] These data sets include: 5 complex

[13] Peters, W.D. *et al.,* 1999. Comparison of Regulatory Design Concentrations: AERMOD vs. ISCST3 and CTDMPLUS, Draft Report. Docket No. A–99–05; II–A–15.

terrain data sets, 7 building downwash data sets, and 5 simple terrain data sets (see appendix A of the Response-to-Comments document [4]). This performance analysis, which is a check of the model's maximum concentration predictions against observed data, includes a comparison of the current version of the new model (AERMOD 02222) with ISC3ST or ISC–PRIME for downwash conditions. The results and conclusions of the performance analyses are presented in 2 sections: Non-downwash and downwash source scenarios.

a. Non-Downwash Cases

For the user community to obtain a full understanding of the impacts of today's proposal for the non-downwash source scenarios (flat and complex terrain), our performance evaluation of AERMOD (02222) must be discussed with respect to the old model, ISC3ST, and with respect to AERMOD (99351). Based on the evaluation, we have concluded that AERMOD (02222) significantly outperforms ISC3ST and that AERMOD (02222)'s performance is even better than that of AERMOD (99351).

Evaluation of AERMOD (99351)

Comparative performance statistics were calculated for both ISC3ST and AERMOD (99351) using data sets in non-downwash conditions. This analysis looked at combinations of test sites (flat and complex terrain), pollutants, and concentration averaging times. Comparisons indicated very significant improvements in performance when applying AERMOD (99351). In all but 1 of the total of 20 cases in which AERMOD (99351) could be compared to ISC3ST, AERMOD performed as well as (but generally better than) ISC3ST, that is, AERMOD predicted maximum concentrations that were closer to the measured maximum concentrations. In the most dramatic case (*i.e.*, Lovett; 24-hr) in which AERMOD performed better than ISC3ST, AERMOD's maximum concentration predictions were about the same as the measured concentrations while the ISC3ST's predicted maximum concentrations were about 9 times higher than the measured concentrations. In the one case (*i.e.*, Clifty Creek; 3-hr) where ISC3ST performed better than AERMOD (99351), ISC3ST's concentration predictions matched the observed data and the AERMOD concentration predictions were about 25% higher than the observed data. These results were reported in the supporting documentation for AERMOD (99351).

Evaluation of AERMOD (02222)

With the changes to AERMOD (99351) as outlined above, how has the performance of the AERMOD been affected? The performance of the current version of AERMOD is about the same or slightly better than the April 2000 version when a comparison is made over all the available data sets. There were examples of AERMOD (02222) showing better and poorer performance when compared to the performance results of AERMOD (99351). However, for those cases where AERMOD (02222)'s performance was degraded, the degradation was small. On the other side, there were more examples where AERMOD (02222) more closely predicted measured concentrations. The performance improvements were also rather small but, in general, were somewhat larger than the size of the performance degradations. There also were a number of cases where the performance remained unchanged between the 2 models. Thus, overall, there was a slight improvement in AERMOD's performance and, consequently, we believe that AERMOD (02222) significantly outperforms ISC3ST for non-downwash source scenarios.

For AERMOD (02222) with the 5 data bases examined for simple terrain, the ratios of modeled/observed Robust High Concentration ranged from 0.77 to 1.11 (1-hr average), 0.98 to 1.24 (3-hr average), 0.94 to 0.97 (24-hr average) and 0.30 to 0.97 (annual average). These ratios reflect better performance than ISC3ST for all cases.

For AERMOD (02222) with the 5 data bases examined for complex terrain, these ratios ranged from 1.03 to 1.12 (3-hr average), 0.67 to 1.78 (24-hr average) and 0.54 to 1.59 (annual average). At Tracy—the only site for which there are 1-hr data—AERMOD performed considerably better (ratio = 1.04) than either ISC3ST or CTDMPLUS. At three of the other four sites, AERMOD generally performed much better than either ISC3ST or (where applicable) alternative models for the 3-hr and 24-hr averaging times; results were comparable for Clifty Creek (for the 3-hr averaging times, AERMOD (02222) predictions were only about 5% higher than ISC3ST's—down from 25% for AERMOD (99351) as described earlier). At the two sites where annual peak comparisons are available, AERMOD performed much better than either ISC3ST or alternative models.

b. Downwash Cases

For the downwash data sets, there were combinations of test sites, pollutants, stack heights and averaging times where the proposed (ISC–PRIME) model performance could be compared to the performance of AERMOD (02222) with PRIME incorporated. There was an equal number of non-downwash cases where AERMOD performed better than ISC–PRIME and where ISC–PRIME performed better than AERMOD. There was only one case where there was a significant difference between the two models' performance, and AERMOD clearly performed better than ISC–PRIME in this case. In all other cases, the difference in the performance, whether an improvement or a degradation, was small. This comparison indicated that AERMOD (02222) performs very similarly, if not somewhat better, when compared to ISC–PRIME for downwash cases.

2. Analysis of Regulatory Design Concentrations for AERMOD (02222)

Although not a performance tool, the analysis of design concentrations (''consequence'' analysis) is designed to test model stability and continuity, and to help the user community understand the differences to be expected between air dispersion models. The consequences, or changes in the regulatory concentrations predicted when using the new model (AERMOD 02222) versus ISC3ST, cover 96 source scenarios and at least 3 averaging periods per source scenario, and are evaluated and summarized here. The purpose is to provide the user community with a sense of potential changes in their air dispersion analyses when applying the new model over a broad range of source types and settings. The *consequence analysis*, in which AERMOD was run for hundreds of source scenarios, also provides a check for model stability (abnormal halting of model executions when using valid control files and input data) and for spurious results (unusually high or low concentration predictions which are unexplained). The results are placed into 3 categories: non-downwash source scenarios in flat, simple terrain; downwash source scenarios in flat terrain; and, complex terrain source settings. The focus of this discussion is on how design concentrations change from those predicted by ISC3ST when applying the latest version of AERMOD versus applying the earlier version of AERMOD (99351).

a. Non-Downwash Cases

For the non-downwash situations, there were 48 cases covering a variety of source types (point, area, and volume sources), stack heights, terrain types (flat and simple), and dispersion settings (urban and rural). For each case in the consequence analysis, we calculated the ratio between AERMOD's regulatory concentration predictions and ISC3ST's regulatory concentration predictions. The average ratio of AERMOD to ISC3ST-predicted concentrations changed from 1.14 when applying AERMOD (99351) to 0.96 when applying AERMOD (02222).[14] Thus, in general, AERMOD (02222) tends to predict concentrations closer to ISC3ST than does version 99351 proposed in April 2000. Also, the variation of the differences between ISC3ST and AERMOD has decreased with AERMOD (02222). Comparing the earlier consequence analysis to the latest study with AERMOD (02222), we saw a 25% reduction in the number of cases where the AERMOD-predicted concentrations differed by over a factor of two from ISC3ST's predictions.

b. Downwash Cases

For the downwash analysis, there were 20 cases covering a range of stack heights, locations of stacks relative to the building, dispersion settings, and building shapes. As before, we calculated the ratio regulatory concentration predictions from AERMOD (02222 with PRIME) and compared them as ratios to those from ISC3ST for each case. For additional information, we also included ratios with ISC–PRIME that was also proposed in April 2000.

Calculated over all the 20 cases, and for all averaging times considered, the average ISC–PRIME to ISC3ST concentration ratio is about 0.86, whereas for AERMOD (PRIME) to ISC3ST, it is 0.82. The maximum value of the concentration ratios range from 2.24 for ISC–PRIME/ISC3ST to 3.67 for AERMOD (PRIME)/ISC3ST. Similarly, the minimum value of the concentration ratio range from 0.04 for ISC–PRIME/ ISC3ST to 0.08 for AERMOD (PRIME)/ ISC3ST. (See Table 4–5 in reference 12.)

Although results above for the two models that use PRIME—AERMOD (02222) and ISC–PRIME—show differences, we find that building downwash is not a significant factor in determining the maximum concentrations in some of the cases, *i.e.*, the PRIME algorithms do not predict a building cavity concentration. Of those cases where downwash was important, the average concentration ratios of ISC–PRIME/ISC3ST and AERMOD (02222)/ ISC3ST are about 1. The maximum value of the concentration ratios range from 2.24 for ISC–PRIME/ISC3ST to 1.87 for AERMOD (02222)/ISC3ST and the minimum value of the concentration ratios range from 0.34 for ISC–PRIME/ ISC3ST to 0.38 for AERMOD (02222)/ ISC3ST. These results show relatively close agreement between the two PRIME models. (*See* Table 4–6 in reference 12.)

ISC3ST does not predict cavity concentrations but comparisons can be made between AERMOD and ISC–PRIME. The average AERMOD (02222) predicted 1-hour cavity concentration is about the same (112%) as the average ISC–PRIME 1-hour cavity concentration. In the extremes, the AERMOD (02222)-predicted cavity concentrations ranged from about 40% higher to 15% lower than the corresponding ISC–PRIME cavity concentration predictions. Thus, in general, where downwash is a significant factor, AERMOD (02222) and ISC–PRIME predict similar maximum concentrations. (*See* Table 4–8 in reference 12.)

Although the same downwash algorithms are used in both models, there are differences in the melding of PRIME with the core model, and differences in the way that these models simulate the atmosphere.[15] The downwash algorithm implementation therefore could not be exactly the same.

c. Complex Terrain

During the testing of AERMOD after modifications were made to the complex terrain algorithm (*see* discussion of hill height scale (h_C) in B. Appropriate for Proposed Use in this preamble), a small error was found in the original complex terrain code while conducting the consequence analysis. This error was subsequently repaired. Final testing indicated that the revised complex terrain code produced reasonable results for the consequence analysis, as described below.

The analysis of predicted design concentrations included a suite of complex terrain settings. There were 28 cases covering a variety of stack heights, stack gas buoyancy values, types of hills, and distances between source and terrain. The ratios between the AERMOD (02222 & 99351)—predicted maximum concentrations and the ISC3ST maximum concentrations were calculated for all cases for a series of averaging times. When comparing AERMOD (99351) to ISC3ST and then AERMOD (02222) to ISC3ST, the average maximum concentration ratio, the highest ratios and the lowest ratios were almost unchanged. There were no cases in either consequence analysis where AERMOD (02222 & 99351) predicted higher concentrations than those predicted by ISC3ST. Thus, in general, the consequences of moving from ISC3ST to AERMOD (02222) rather than to AERMOD (99351) in complex terrain were essentially the same. (*See* Table 4–9 in reference 12.)

E. Emission and Dispersion Modeling System (EDMS)

The Emissions and Dispersion Modeling System (EDMS) was developed jointly by the Federal Aviation Administration (FAA) and the U.S. Air Force in the late 1970s and first released in 1985 to assess the air quality of proposed airport development projects. EDMS has an emissions preprocessor and its dispersion module estimates concentrations for various averaging times for the following pollutants: CO, HC, NO_X, SO_X, and suspended particles (*e.g.*, PM–10). The first published application of EDMS was in December 1986 for Stapleton International Airport (FAA–EE–11–A/ REV2).

In 1988, version 4a4 revised the dispersion module to include an integral dispersion submodel: GIMM (Graphical Input Microcomputer Model). This version was proposed for adoption in the *Guideline*'s appendix A in February 1991 (56 FR 5900). This version was included in appendix A in July 1993 (58 FR 38816) and recommended for limited applications for assessments of localized airport impacts on air quality. FAA later updated EDMS to Version 3.0.

In response to the growing needs of air quality analysts and changes in regulations (*e.g.*, conformity requirements from the Clean Air Act Amendment of 1990), FAA updated EDMS to version 3.1, which is based on the CALINE3 [16] and PAL2 dispersion kernels. In our April 2000 NPR we proposed to adopt the version 3.1 update to EDMS. However, this update had not been subjected to performance evaluation and no studies of EDMS' performance have been cited in appendix A of the *Guideline*. Comment was invited on whether this compromises the viability of EDMS 3.1 as a recommended or preferred model and how this deficiency can be corrected.

Several commenters expressed concern about EDMS 3.1 as a recommended model in appendix A. Indeed, there were concerns that EDMS

[14] A ratio of 1.00 indicates that the two models are predicting the same concentrations. See Table 4.1 in reference 12.

[15] AERMOD uses more complex techniques to estimate temperature profiles which, in turn, affect the calculation of the plume rise. Plume rise may affect the cavity and downwash concentrations.

[16] Currently listed in appendix A of the *Guideline*.

3.1 had not been as well validated as other models, nor subjected to peer review, as required by the *Guideline*'s subsection 3.1.1. One of these commenters suggested that EDMS 3.1 should be presented only as one of several alternative models.

At the 7th Conference, FAA proposed for appendix A adoption an even newer, enhanced version of EDMS—version 4.0, which incorporates the AERMOD dispersion kernel (without alteration). In this system, the latest version of AERMOD would be employed as a standalone component of EDMS. This dispersion kernel was to replace PAL2 and CALINE3 currently in EDMS 3.1. There were no public comments specific to FAA's proposed AERMOD-based enhancements to EDMS announced after our April 2000 NPR.

In response to written comments on our April 2000 NPR, at the 7th Conference (transcript) FAA promised a complete evaluation process that would include sensitivity testing, intermodel comparison, and analysis of EDMS predictions against field observations. The intermodel comparisons were proposed for the UK's Atmospheric Dispersion Modeling System (ADMS).[17]

As we explained in our September 8, 2003 Notice of Data Availability, FAA has decided to withdraw EDMS from the *Guideline*'s appendix A. We stated that no new information was therefore provided in that notice, and we affirmed support for EDMS' removal from appendix A. This removal, which we promulgate today, obviates the need for EDMS' documentation and evaluation at this time.

V. Discussion of Public Comments on Our September 8, 2003 Notice of Data Availability

As mentioned in section III, after AERMOD was revised pursuant to comments received on the April 21, 2000 proposal, a Notice of Data Availability (NDA) was issued on September 8, 2003 to explain the modifications and to reveal AERMOD's new evaluation data. Public comments were solicited for 30 days and posted electronically in eDocket OAR–2003–0201.[1] (As mentioned in section IV, additional comments received since we published the final rule on April 15, 2003 are filed in Docket A–99–05; category IV–E.) We summarized these comments and developed detailed responses; these appear as appendix C to the Response-to-Comments document.[4] In appendix C, we considered and discussed all significant comments, developed responses, and documented conclusions on appropriate actions for today's notice. Whenever the comments revealed any new information or suggested any alternative solutions, we considered them in our final action and made corrections or enhancements where appropriate.

In the remainder of this preamble section we highlight the main issues raised by the commenters who reviewed the NDA, and summarize our responses. These comments broadly fall into two categories: technical/operational, and administrative.

The technical/operational comments were varied. One commenter thought EPA's sensitivity studies for simulating area sources were too limited, and noted that AERMOD, when used to simulate an area source adjacent to gently sloping terrain, produced ground-level concentrations not unlike those from ISC3ST. In response we explained qualitatively how AERMOD interprets this situation and cautioned that reviewing authorities should be consulted in such scenarios for guidance on switch settings. Other commenters believed that AERMOD exhibited unrealistic treatment of complex terrain elements and offered supporting data. In response, AERMIC concluded that AERMOD does exhibit terrain amplification factors on the windward side of isolated hills, where impacts are expected to be greatest. Commenters also presented evidence that the PRIME algorithm in AERMOD misbehaves in its treatment of building wake and wind incidence. Another model was cited as having better skill in this regard. In response, we acknowledged this but established that AERMOD's capability was acceptable for handling the majority of building geometries encountered (see Response-to-Comments document[4] for more details).

A number of commenters addressed administrative or procedural matters. Some believed that the transition period for implementation—one year—is too short. We explained in response that one year is consistent with past practice and is adequate for most users and reviewing authorities given our previous experience with new models and the fact that AERMOD has been in the public domain for several years. Some were disappointed that the review period (30 days) for the NDA was too short. We believe that the period was adequate to review the two reports that presented updated information on the performance and practical consequences of the model as revised. Regarding the evaluation/comparison regime used for AERMOD, others objected to the methodology used to evaluate AERMOD (one that emphasizes Robust High Concentration), claiming it is ill-suited to the way dispersion models estimate ambient concentrations. We acknowledged that other methods are available that are designed to reflect the underlying physics and formulations of dispersion models, and may be more robust in their mechanisms to account for the stochastic nature of the atmosphere. In fact, we cited several recent cases from the literature in which such methods were applied in evaluations that included AERMOD. We also explained that the approach taken by AERMIC was based on existing guidance in section 9 of Appendix W, and expressed a commitment to explore other methods in the future, including an update to section 9. We believe however that the evaluation methodology used was reasonable for its intended purpose—examining a large array of concentrations for a wide variety of source types—and confers a measure of consistency given its past use. Other commenters expressed disappointment that AERMOD wasn't compared to state-of-the-science models as advised in its peer review report. In response, we cited a substantial list of studies in which AERMOD has, in fact, been compared to some of these models, *e.g.*, HPDM and ADMS (in various combinations). On the whole, as we noted in our response, AERMOD typically performed as well as HPDM and ADMS, and all of them generally performed better than ISC3ST. Still others expressed disappointment that the evaluation input data weren't posted on our Web site until January 22, 2004—three months after the close of the comment period. We acknowledge that the input data were not posted when the NDA was published. However, the actual evaluation input data for AERMOD had not been requested previously, and we did not believe they were required as a basis for reviewing the reports we released. Moreover, since the posting, we are unaware of any belated adverse comments from anyone attempting to access and use the data.

We believe we have carefully considered and responded to public comments and concerns regarding AERMOD. We have also made efforts to update appendix W to better reflect current practice in model solicitation, evaluation and selection. We also have made other technical revisions so the guidance conforms with the latest form of the PM–10 National Ambient Air Quality Standard.

[17] Cambridge Environmental Research Consultants; *http://www.cerc.co.uk/.*

VI. Final Action

In this section we explain the changes to the *Guideline* in today's action in terms of the main technical and policy concerns addressed by the Agency in its response to public comments (sections IV & V). Air quality modeling involves estimating ambient concentrations using scientific methodologies selected from a range of possible methods, and should utilize the most advanced practical technology that is available at a reasonable cost to users, keeping in mind the intended uses of the modeling and ensuring transparency to the public. With these changes, we believe that the *Guideline* continues to reflect recent advances in the field and balance these important considerations. Today's action amends Appendix W of 40 CFR part 51 as detailed below:

AERMOD

Based on the supporting information contained in the docket, and reflected in peer review and public comments, we find that the AERMOD modeling system and PRIME are based on sound scientific principles and provide significant improvements over the current regulatory model, ISC3ST. AERMOD characterizes plume dispersion better than ISC3ST. The accuracy of the AERMOD system is generally well-documented and superior to that of ISC3ST. We are adopting the model based on its performance and other factors.

Public comments on the April 2000 proposal expressed significant concern about the need to use two models (AERMOD and ISC–PRIME) to simulate just one source when downwash posed a potential impact. In response to this concern we incorporated PRIME into AERMOD and documented satisfactory tests of the algorithm. AERMOD, with the inclusion of PRIME, is now appropriate and practical for regulatory applications.

The state-of-the-science for modeling atmospheric deposition continues to evolve, the best techniques are currently being assessed, and their results are being compared with observations. Consequently, as we now say in *Guideline* paragraph 4.2.2(c), the approach taken for any regulatory purpose should be coordinated with the appropriate reviewing authority. We agreed with the public comments calling for the addition of state-of-the-science deposition algorithms, and developed a modification to AERMOD (02222) for *beta* testing. This model, AERMOD (04079) was posted on our Web site *http://www.epa.gov/scram001/tt25.htm#aermoddep* on March 19, 2004. The latest version of AERMOD may now be used for deposition analysis in special situations.

Since AERMOD treats dispersion in complex terrain, we have merged sections 4 and 5 of appendix W, as proposed in the April 2000 NPR. And while AERMOD produces acceptable regulatory design concentrations in complex terrain, it does not replace CTDMPLUS for detailed or receptor-oriented complex terrain analysis, as we have made clear in *Guideline* section 4.2.2. CTDMPLUS remains available for use in complex terrain.

We have implemented the majority of suggestions to improve the AERMET, AERMAP, and AERMOD source code to reflect all the latest features that have been available in ISC3ST and that are available in the latest versions of Fortran compilers. Also, the latest formats for meteorological and terrain input data are now accepted by the new versions of AERMET and AERMAP. Our guidance, documentation and users' guides have been modified in response to a number of detailed comments.

With respect to AERMOD (02222)'s performance, we have concluded that:

(1) AERMOD (99351), the version proposed in April 2000, performs significantly better than ISC3ST, and AERMOD (02222) performs slightly better than AERMOD (99351) in non-downwash settings in both simple and complex terrain;

(2) The performance evaluation indicates that AERMOD (02222) performs slightly better than ISC–PRIME for downwash cases.

With respect to changes in AERMOD's regulatory design concentrations compared to those for ISC3ST, we have concluded that:

- For non-downwash settings, AERMOD (02222), on average, tends to predict concentrations closer to ISC3ST, and with somewhat smaller variations, than the April 2000 proposal of AERMOD;
- Where downwash is a significant factor in the air dispersion analysis, AERMOD (02222) predicts maximum concentrations that are very similar to ISC–PRIME's predictions;
- For those source scenarios where maximum 1-hour cavity concentrations are calculated, the average AERMOD (02222)-predicted cavity concentration tends to be about the same as the average ISC–PRIME cavity concentrations; and
- In complex terrain, the consequences of using AERMOD (02222) instead of ISC3ST remained essentially unchanged in general, although they varied based on individual circumstances.

Since AERMOD (02222) was released, an updated version was posted on our Web site on March 22, 2004: AERMOD (04079). The version we are releasing pursuant to today's promulgation, however, is AERMOD (04300). This version, consonant with AERMOD (02222) in its formulations, addresses the following minor code issues:

- The area source algorithm in simple and complex terrain required a correction to the way the dividing streamline height is calculated.
- In PRIME, incorrect turbulence parameters were being passed to one of the numerical plume rise routines, and this has been corrected.
- A limit has been placed on plume cooling within PRIME to avoid supercooling, which had been causing runtime instability.
- A correction has been made to avoid AERMOD's termination under certain situations with capped stacks (i.e., where the routine was attempting to take a square root of a negative number). Our testing has demonstrated only very minor impacts from these corrections on the evaluation results or the consequence analysis.

AERMOD (04300) has other draft portions of code that represent options not required for regulatory applications. These include:

- Dry and wet deposition for both gases and particles;
- The ozone limiting method (OLM), referenced in section 5.2.4 (Models for Nitrogen Dioxide—Annual Average) of the *Guideline* for treating NO_X conversion; and
- The Plume Volume Molar Ratio Method (PVMRM) for treating NO_X conversion.
- The bulk Richardson number approach (discussed earlier) for using near-surface temperature difference has been corrected in AERMOD (04300).

Based on the technical information contained in the docket for this rule, and with consideration of the performance analysis in combination with the analysis of design concentrations, we believe that AERMOD is appropriate for regulatory use and we are revising the *Guideline* to adopt it as a refined model today.

In implementing the changes to the *Guideline*, we recognize that there may arise occasions in which the application of a new model can result in the discovery by a permit applicant of previously unknown violations of NAAQS or PSD increments due to emissions from existing nearby sources. This potential has been acknowledged previously and is addressed in existing EPA guidance (''Air Quality Analysis for Prevention of Significant Deterioration

(PSD),'' Gerald A. Emison, July 5, 1988). To summarize briefly, the guidance identifies three possible outcomes of modeling by a permit applicant and details actions that should be taken in response to each:

1. Where dispersion modeling shows no violation of a NAAQS or PSD increment in the impact area of the proposed source, a permit may be issued and no further action is required.

2. Where dispersion modeling predicts a violation of a NAAQS or PSD increment within the impact area but it is determined that the proposed source will not have a significant impact (i.e., will not be above de minimis levels) at the point and time of the modeled violation, then the permit may be issued immediately, but the State must take appropriate actions to remedy the violations within a timely manner.

3. Where dispersion modeling predicts a violation of a NAAQS or PSD increment within the impact area and it is determined that the proposed source will have a significant impact at the point and time of the modeled violation, then the permit may not be issued until the source owner or operator eliminates or reduces that impact below significance levels through additional controls or emissions offsets. Once it does so, then the permit may be issued even if the violation persists after the source owner or operator eliminates its contribution, but the State must take further appropriate actions at nearby sources to eliminate the violations within a timely manner.

In previous promulgations, we have traditionally allowed a one-year transition (''grandfather'') period for new refined techniques. Accordingly, for appropriate applications, AERMOD *may be* substituted for ISC3 during the one-year period following the promulgation of today's notice. Beginning one year after promulgation of today's notice, (1) applications of ISC3 with approved protocols may be accepted (see **DATES** section) and (2) AERMOD *should be* used for appropriate applications as a replacement for ISC3.

We separately issue guidance for use of modeling for facility-specific and community-scale air toxics risk assessments through the Air Toxics Risk Assessment Reference Library.[18] We recognize that the tools and approaches recommended therein will eventually reflect the improved formulations of the AERMOD modeling system and we expect to appropriately incorporate them as expeditiously as practicable. In the interim, as appropriate, we will consider the use of either ISC3 or AERMOD in air toxic risk assessment applications.

EDMS

FAA has completed development of the new EDMS4.0 to incorporate AERMOD. The result is a conforming enhancement that offers a stronger scientific basis for air quality modeling. FAA has made this model available on its Web site, which we cite in an updated *Guideline* paragraph 7.2.4(c). As described earlier in this preamble, the summary description for EDMS will be removed from appendix A.

VII. Final Editorial Changes to Appendix W

Today's update of the *Guideline* takes the form of many revisions, and some of the text is unaltered. Therefore, as a purely practical matter, we have chosen to publish the new version of the entire text of appendix W and its appendix A. Guidance and editorial changes associated with the resolution of the issues discussed in the previous section are adopted in the appropriate sections of the *Guideline*, as follows:

Preface

You will note some minor revisions of appendix W to reflect current EPA practice.

Section 4

As mentioned earlier, we revised section 4 to present AERMOD as a refined regulatory modeling technique for particular applications.

Section 5

As mentioned above, we merged pertinent guidance in section 5 (Modeling in Complex Terrain) with that in section 4. With the anticipated widespread use of AERMOD for all terrain types, there is no longer any utility in the previous differentiation between simple and complex terrain for model selection. To further simplify, the list of acceptable, yet equivalent, screening techniques for complex terrain was removed. CTSCREEN and guidance for its use are retained; CTSCREEN remains acceptable for all terrain above stack top. The screening techniques whose descriptions we removed, i.e., Valley (as implemented in SCREEN3), COMPLEX I (as implemented in ISC3ST), and RTDM remain available for use in applicable cases where established/accepted procedures are used. Consultation with the appropriate reviewing authority is still advised for application of these screening models.

Section 6

As proposed, we renumbered this to become section 5. In subsection 5.1, we reference the Plume Volume Molar Ratio Method (PVMRM) for point sources of NO_X, and mention that it is currently being tested to determine suitability as a refined method.

Section 7

As proposed, we renumbered this to become section 6. We updated the reference to the Emissions and Dispersion Modeling System (EDMS).

Section 8

As proposed, we revised section 8 (renumbered to section 7) to provide guidance for using AERMET (AERMOD's meteorological preprocessor).

- In subsection 7.2.4, we introduce the atmospheric stability characterization for AERMOD.
- In subsection 7.2.5, we describe the plume rise approaches used by AERMOD.

Section 9

As proposed, we renumbered section 9 to become section 8. We added paragraphs 8.3.1.2(e) and 8.3.1.2(f) to clarify use of site specific meteorological data for driving CALMET in the separate circumstances of long range transport and for complex terrain applications.

Section 10

As proposed, we revised section 10 (renumbered section 9) to include AERMOD. In May 1999, the D.C. Court of Appeals vacated the PM–10 standard we promulgated in 1997, and this standard has since been removed from the CFR (69 FR 45592; July 30, 2004). Paragraph 10.2.3.2(a) has been corrected to be consistent with the current (original) PM–10 standard, which is based on expected exceedances.

Section 11

As proposed, we renumbered section 11 to become section 10.

Sections 12 & 13

We renumbered section 12 to become section 11, and section 13 (References) to become section 12. We revised renumbered section 12 by adding some references, deleting obsolete/superseded ones, and resequencing. You will note that the peer scientific review for AERMOD and latest evaluation references have been included.

Appendix A

We added AERMOD (with the PRIME downwash algorithm integrated) to

[18] *http://www.epa.gov/ttn/fera/risk_atra_main.html.*

appendix A. We removed EDMS from appendix A. We also updated the description for CALPUFF, and made minor updates to some of the other model descriptions.

Availability of Related Information

Our Air Quality Modeling Group maintains an Internet Web site (Support Center for Regulatory Air Models—SCRAM) at: *http://www.epa.gov/scram001.* You may find codes and documentation for models referenced in today's action on the SCRAM Web site. In addition, we have uploaded various support documents (e.g., evaluation reports).

VIII. Statutory and Executive Order Reviews

A. Executive Order 12866: Regulatory Planning and Review

Under Executive Order 12866 [58 FR 51735 (October 4, 1993)], the Agency must determine whether the regulatory action is ''significant'' and therefore subject to review by the Office of Management and Budget (OMB) and the requirements of the Executive Order. The Order defines ''significant regulatory action'' as one that is likely to result in a rule that may:

(1) Have an annual effect on the economy of $100 million or more or adversely affect in a material way the economy, a sector of the economy, productivity, competition, jobs, the environment, public health or safety, or State, local, or tribal governments or communities;

(2) Create a serious inconsistency or otherwise interfere with an action taken or planned by another agency;

(3) Materially alter the budgetary impact of entitlements, grants, user fees, or loan programs of the rights and obligations of recipients thereof; or

(4) Raise novel legal or policy issues arising out of legal mandates, the President's priorities, or the principles set forth in the Executive Order.

It has been determined that this rule is not a ''significant regulatory action'' under the terms of Executive Order 12866 and is therefore not subject to EO 12866 review.

B. Paperwork Reduction Act

This final rule does not contain any information collection requirements subject to review by OMB under the Paperwork Reduction Act, 44 U.S.C. 3501 *et seq.*

Burden means the total time, effort, or financial resources expended by persons to generate, maintain, retain, or disclose or provide information to or for a Federal agency. This includes the time needed to review instructions; develop, acquire, install, and utilize technology and systems for the purposes of collecting, validating, and verifying information, processing and maintaining information, and disclosing and providing information; adjust the existing ways to comply with any previously applicable instructions and requirements; train personnel to be able to respond to a collection of information; search data sources; complete and review the collection of information; and transmit or otherwise disclose the information.

An agency may not conduct or sponsor, and a person is not required to respond to a collection of information unless it displays a currently valid OMB control number. The OMB control numbers for EPA's regulations in 40 CFR are listed in 40 CFR part 9.

C. Regulatory Flexibility Act (RFA)

The RFA generally requires an agency to prepare a regulatory flexibility analysis of any rule subject to notice and comment rulemaking requirements under the Administrative Procedure Act or any other statute unless the agency certifies that the rule will not have a significant economic impact on a substantial number of small entities. Small entities include small businesses, small organizations, and small governmental jurisdictions.

For purposes of assessing the impact of today's rule on small entities, small entities are defined as: (1) A small business that meets the RFA default definitions for small business (based on Small Business Administration size standards), as described in 13 CFR 121.201; (2) a small governmental jurisdiction that is a government of a city, county, town, school district or special district with a population of less than 50,000; and (3) a small organization that is any not-for-profit enterprise which is independently owned and operated and is not dominant in its field.

After considering the economic impacts of today's final rule on small entities, I certify that this action will not have a significant economic impact on a substantial number of small entities. As this rule merely updates existing technical requirements for air quality modeling analyses mandated by various CAA programs (e.g., prevention of significant deterioration, new source review, State Implementation Plan revisions) and imposes no new regulatory burdens, there will be no additional impact on small entities regarding reporting, recordkeeping, and compliance requirements.

D. Unfunded Mandates Reform Act of 1995

Title II of the Unfunded Mandates Reform Act of 1995 (UMRA), Public Law 104–4, establishes requirements for Federal agencies to assess the effects of their regulatory actions on State, local, and tribal governments and the private sector. Under section 202 of the UMRA, EPA generally must prepare a written statement, including a cost-benefit analysis, for proposed and final rules with ''Federal mandates'' that may result in expenditures to State, local, and tribal governments, in the aggregate, or to the private sector, of $100 million or more in any one year. Before promulgating an EPA rule for which a written statement is needed, section 205 of the UMRA generally requires EPA to identify and consider a reasonable number of regulatory alternatives and adopt the least costly, most cost-effective or least burdensome alternative that achieves the objectives of the rule. The provisions of section 205 do not apply when they are inconsistent with applicable law. Moreover, section 205 allows EPA to adopt an alternative other than the least costly, most cost-effective or least burdensome alternative if the Administrator publishes with the final rule an explanation why that alternative was not adopted. Before EPA establishes any regulatory requirements that may significantly or uniquely affect small governments, including tribal governments, it must have developed under section 203 of the UMRA a small government agency plan.

The plan must provide for notifying potentially affected small governments, enabling officials of affected small governments to have meaningful and timely input in the development of EPA regulatory proposals with significant Federal intergovernmental mandates, and informing, educating, and advising small governments on compliance with the regulatory requirements.

Today's rule recommends a new modeling system, AERMOD, to replace ISC3ST as an analytical tool for use in SIP revisions and for calculating PSD increment consumption. AERMOD has been used for these purposes on a case-by-case basis (per *Guideline* subsection 3.2.2) for several years. Since the two modeling systems are comparable in scope and purpose, use of AERMOD itself does not involve any significant increase in costs. Moreover, modeling costs (which include those for input data acquisition) are typically among the implementation costs that are considered as part of the programs (*i.e.*, PSD) that establish and periodically revise requirements for compliance.

Any incremental modeling costs attributable to today's rule do not approach the $100 million threshold prescribed by UMRA. EPA has determined that this rule contains no regulatory requirements that might significantly or uniquely affect small governments. This rule therefore contains no Federal mandates (under the regulatory provisions of Title II of the UMRA) for State, local, or tribal governments or the private sector.

E. Executive Order 13132: Federalism

Executive Order 13132, entitled ''Federalism'' (64 FR 43255, August 10, 1999), requires EPA to develop an accountable process to ensure ''meaningful and timely input by State and local officials in the development of regulatory policies that have federalism implications.'' ''Policies that have federalism implications'' is defined in the Executive Order to include regulations that have ''substantial direct effects on the States, on the relationship between the national government and the States, or on the distribution of power and responsibilities among the various levels of government.''

This final rule does not have federalism implications. It will not have substantial direct effects on the States, on the relationship between the national government and the States, or on the distribution of power and responsibilities among the various levels of government, as specified in Executive Order 13132. This rule does not create a mandate on State, local or tribal governments. The rule does not impose any enforceable duties on these entities (*see* D. Unfunded Mandates Reform Act of 1995, above). The rule would add better, more accurate techniques for air dispersion modeling analyses and does not impose any additional requirements for any of the affected parties covered under Executive Order 13132. Thus, Executive Order 13132 does not apply to this rule.

F. Executive Order 13175: Consultation and Coordination With Indian Tribal Governments

Executive Order 13175, entitled ''Consultation and Coordination with Indian Tribal Governments'' (65 FR 67249, November 9, 2000), requires EPA to develop an accountable process to ensure ''meaningful and timely input by tribal officials in the development of regulatory policies that have tribal implications.'' This final rule does not have tribal implications, as specified in Executive Order 13175. As stated above (*see* D. Unfunded Mandates Reform Act of 1995, above), the rule does not impose any new requirements for calculating PSD increment consumption, and does not impose any additional requirements for the regulated community, including Indian Tribal Governments. Thus, Executive Order 13175 does not apply to this rule.

Today's final rule does not significantly or uniquely affect the communities of Indian tribal governments. Accordingly, the requirements of section 3(b) of Executive Order 13175 do not apply to this rule.

G. Executive Order 13045: Protection of Children From Environmental Health and Safety Risks

Executive Order 13045 applies to any rule that EPA determines (1) to be ''economically significant'' as defined under Executive Order 12866, and (2) the environmental health or safety risk addressed by the rule has a disproportionate effect on children. If the regulatory action meets both the criteria, the Agency must evaluate the environmental health or safety effects of the planned rule on children; and explain why the planned regulation is preferable to other potentially effective and reasonably feasible alternatives considered by the Agency.

This final rule is not subject to Executive Order 13045, entitled ''Protection of Children from Environmental Health Risks and Safety Risks'' (62 FR 19885, April 23, 1997) because it does not impose an economically significant regulatory action as defined by Executive Order 12866 and the action does not involve decisions on environmental health or safety risks that may disproportionately affect children.

H. Executive Order 13211: Actions That Significantly Affect Energy Supply, Distribution, or Use

This rule is not subject to Executive Order 13211, ''Actions Concerning Regulations That Significantly Affect Energy Supply, Distribution, or Use'' (66 FR 28355 (May 22, 2001)) because it is not a significant regulatory action under Executive Order 12866.

I. National Technology Transfer and Advancement Act of 1995

Section 12(d) of the National Technology Transfer and Advancement Act of 1995 (''NTTAA''), Public Law 104–113, section 12(d) (15 U.S.C. 272 note) directs EPA to use voluntary consensus standards in its regulatory activities unless to do so would be inconsistent with applicable law or otherwise impractical. Voluntary consensus standards are technical standards (*e.g.*, materials specifications, test methods, sampling procedures, and business practices) that are developed or adopted by voluntary consensus standards bodies. The NTTAA directs EPA to provide Congress, through OMB, explanations when the Agency decides not to use available and applicable voluntary consensus standards.

This action does not involve technical standards. Therefore, EPA did not consider the use of any voluntary consensus standards.

J. Congressional Review Act of 1998

The Congressional Review Act, 5 U.S.C. 801 *et seq.*, as added by the Small Business Regulatory Enforcement Fairness Act of 1996, generally provides that before a rule may take effect, the agency promulgating the rule must submit a rule report, which includes a copy of the rule, to each House of the Congress and to the Comptroller General of the United States. EPA will submit a report containing this rule and other required information to the U.S. Senate, the U.S. House of Representatives, and the Comptroller General of the United States prior to publication of the rule in the **Federal Register**. A Major rule cannot take effect until 60 days after it is published in the **Federal Register**. This action is not a ''major rule'' as defined by 5 U.S.C. 804(2), and will be effective 30 days from the publication date of this notice.

List of Subjects in 40 CFR Part 51

Environmental protection, Administrative practice and procedure, Air pollution control, Carbon monoxide, Intergovernmental relations, Nitrogen oxides, Ozone, Particulate Matter, Reporting and recordkeeping requirements, Sulfur oxides.

Dated: October 21, 2005.

Stephen L. Johnson,

Administrator.

■ Part 51, chapter I, title 40 of the Code of Federal Regulations is amended as follows:

PART 51—REQUIREMENTS FOR PREPARATION, ADOPTION, AND SUBMITTAL OF IMPLEMENTATION PLANS

■ 1. The authority citation for part 51 continues to read as follows:

Authority: 23 U.S.C. 100; 42 U.S.C. 7401–7671q.

■ 2. Appendix W to Part 51 revised to read as follows:

Appendix W to Part 51—Guideline on Air Quality Models

Preface

a. Industry and control agencies have long expressed a need for consistency in the application of air quality models for regulatory purposes. In the 1977 Clean Air Act, Congress mandated such consistency and encouraged the standardization of model applications. The *Guideline on Air Quality Models* (hereafter, *Guideline*) was first published in April 1978 to satisfy these requirements by specifying models and providing guidance for their use. The *Guideline* provides a common basis for estimating the air quality concentrations of criteria pollutants used in assessing control strategies and developing emission limits.

b. The continuing development of new air quality models in response to regulatory requirements and the expanded requirements for models to cover even more complex problems have emphasized the need for periodic review and update of guidance on these techniques. Historically, three primary activities have provided direct input to revisions of the *Guideline*. The first is a series of annual EPA workshops conducted for the purpose of ensuring consistency and providing clarification in the application of models. The second activity was the solicitation and review of new models from the technical and user community. In the March 27, 1980 **Federal Register**, a procedure was outlined for the submittal to EPA of privately developed models. After extensive evaluation and scientific review, these models, as well as those made available by EPA, have been considered for recognition in the *Guideline*. The third activity is the extensive on-going research efforts by EPA and others in air quality and meteorological modeling.

c. Based primarily on these three activities, new sections and topics have been included as needed. EPA does not make changes to the guidance on a predetermined schedule, but rather on an as-needed basis. EPA believes that revisions of the *Guideline* should be timely and responsive to user needs and should involve public participation to the greatest possible extent. All future changes to the guidance will be proposed and finalized in the **Federal Register**. Information on the current status of modeling guidance can always be obtained from EPA's Regional Offices.

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1.0 Introduction

a. The *Guideline* recommends air quality modeling techniques that should be applied to State Implementation Plan (SIP) revisions for existing sources and to new source reviews (NSR), including prevention of significant deterioration (PSD).[1 2 3] Applicable only to criteria air pollutants, it is intended for use by EPA Regional Offices in judging the adequacy of modeling analyses performed by EPA, State and local agencies and by industry. The guidance is appropriate for use by other Federal agencies and by State agencies with air quality and land management responsibilities. The *Guideline* serves to identify, for all interested parties, those techniques and data bases EPA considers acceptable. The *Guideline* is not intended to be a compendium of modeling techniques. Rather, it should serve as a common measure of acceptable technical analysis when supported by sound scientific judgment.

b. Due to limitations in the spatial and temporal coverage of air quality measurements, monitoring data normally are not sufficient as the sole basis for demonstrating the adequacy of emission limits for existing sources. Also, the impacts of new sources that do not yet exist can only be determined through modeling. Thus, models, while uniquely filling one program need, have become a primary analytical tool in most air quality assessments. Air quality measurements can be used in a complementary manner to dispersion models, with due regard for the strengths and weaknesses of both analysis techniques. Measurements are particularly useful in assessing the accuracy of model estimates. The use of air quality measurements alone however could be preferable, as detailed in a later section of this document, when models are found to be unacceptable and monitoring data with sufficient spatial and temporal coverage are available.

c. It would be advantageous to categorize the various regulatory programs and to apply a designated model to each proposed source needing analysis under a given program. However, the diversity of the nation's topography and climate, and variations in source configurations and operating characteristics dictate against a strict modeling ''cookbook''. There is no one model capable of properly addressing all conceivable situations even within a broad category such as point sources. Meteorological phenomena associated with threats to air quality standards are rarely amenable to a single mathematical treatment; thus, case-by-case analysis and judgment are frequently required. As modeling efforts become more complex, it is increasingly important that they be directed by highly competent individuals with a broad range of experience and knowledge in air quality meteorology. Further, they should be coordinated closely with specialists in emissions characteristics, air monitoring and data processing. The judgment of experienced meteorologists and analysts is essential.

d. The model that most accurately estimates concentrations in the area of interest is always sought. However, it is clear from the needs expressed by the States and EPA Regional Offices, by many industries and trade associations, and also by the deliberations of Congress, that consistency in the selection and application of models and data bases should also be sought, even in case-by-case analyses. Consistency ensures that air quality control agencies and the general public have a common basis for estimating pollutant concentrations, assessing control strategies and specifying emission limits. Such consistency is not, however, promoted at the expense of model and data base accuracy. The *Guideline* provides a consistent basis for selection of the most accurate models and data bases for use in air quality assessments.

e. Recommendations are made in the *Guideline* concerning air quality models, data bases, requirements for concentration estimates, the use of measured data in lieu of model estimates, and model evaluation procedures. Models are identified for some specific applications. The guidance provided here should be followed in air quality analyses relative to State Implementation Plans and in supporting analyses required by EPA, State and local agency air programs. EPA may approve the use of another technique that can be demonstrated to be more appropriate than those recommended in this guide. This is discussed at greater length in Section 3. In all cases, the model applied to a given situation should be the one that provides the most accurate representation of atmospheric transport, dispersion, and chemical transformations in the area of interest. However, to ensure consistency, deviations from this guide should be carefully documented and fully supported.

f. From time to time situations arise requiring clarification of the intent of the guidance on a specific topic. Periodic workshops are held with the headquarters, Regional Office, State, and local agency modeling representatives to ensure consistency in modeling guidance and to promote the use of more accurate air quality models and data bases. The workshops serve to provide further explanations of *Guideline* requirements to the Regional Offices and workshop reports are issued with this clarifying information. In addition, findings from ongoing research programs, new model development, or results from model evaluations and applications are continuously evaluated. Based on this information changes in the guidance may be indicated.

g. All changes to the *Guideline* must follow rulemaking requirements since the *Guideline* is codified in Appendix W of Part 51. EPA will promulgate proposed and final rules in the **Federal Register** to amend this Appendix. Ample opportunity for public comment will be provided for each proposed change and public hearings scheduled if requested.

h. A wide range of topics on modeling and data bases are discussed in the *Guideline*. Section 2 gives an overview of models and their appropriate use. Section 3 provides specific guidance on the use of ''preferred'' air quality models and on the selection of alternative techniques. Sections 4 through 7 provide recommendations on modeling techniques for application to simple-terrain stationary source problems, complex terrain problems, and mobile source problems. Specific modeling requirements for selected regulatory issues are also addressed. Section 8 discusses issues common to many modeling analyses, including acceptable model components. Section 9 makes recommendations for data inputs to models including source, meteorological and background air quality data. Section 10 covers the uncertainty in model estimates and how that information can be useful to the regulatory decision-maker. The last chapter summarizes how estimates and measurements of air quality are used in assessing source impact and in evaluating control strategies.

i. Appendix W to 40 CFR Part 51 itself contains an appendix: Appendix A. Thus, when reference is made to ''Appendix A'' in this document, it refers to Appendix A to Appendix W to 40 CFR Part 51. Appendix A contains summaries of refined air quality models that are ''preferred'' for specific applications; both EPA models and models developed by others are included.

2.0 Overview of Model Use

a. Before attempting to implement the guidance contained in this document, the reader should be aware of certain general information concerning air quality models and their use. Such information is provided in this section.

2.1 Suitability of Models

a. The extent to which a specific air quality model is suitable for the evaluation of source impact depends upon several factors. These include: (1) The meteorological and topographic complexities of the area; (2) the level of detail and accuracy needed for the analysis; (3) the technical competence of those undertaking such simulation modeling; (4) the resources available; and (5) the detail and accuracy of the data base, *i.e.*, emissions inventory, meteorological data, and air quality data. Appropriate data should be available before any attempt is made to apply a model. A model that requires detailed, precise, input data should not be used when such data are unavailable. However, assuming the data are adequate, the greater the detail with which a model considers the spatial and temporal variations in emissions and meteorological conditions, the greater the ability to evaluate the source impact and to distinguish the effects of various control strategies.

b. Air quality models have been applied with the most accuracy, or the least degree of uncertainty, to simulations of long term averages in areas with relatively simple topography. Areas subject to major topographic influences experience meteorological complexities that are extremely difficult to simulate. Although models are available for such circumstances, they are frequently site specific and resource intensive. In the absence of a model capable of simulating such complexities, only a preliminary approximation may be feasible until such time as better models and data bases become available.

c. Models are highly specialized tools. Competent and experienced personnel are an essential prerequisite to the successful application of simulation models. The need for specialists is critical when the more sophisticated models are used or the area being investigated has complicated meteorological or topographic features. A model applied improperly, or with inappropriate data, can lead to serious misjudgements regarding the source impact or the effectiveness of a control strategy.

d. The resource demands generated by use of air quality models vary widely depending on the specific application. The resources required depend on the nature of the model and its complexity, the detail of the data base, the difficulty of the application, and the amount and level of expertise required. The costs of manpower and computational facilities may also be important factors in the selection and use of a model for a specific analysis. However, it should be recognized that under some sets of physical circumstances and accuracy requirements, no present model may be appropriate. Thus, consideration of these factors should lead to selection of an appropriate model.

2.2 Levels of Sophistication of Models

a. There are two levels of sophistication of models. The first level consists of relatively simple estimation techniques that generally use preset, worst-case meteorological conditions to provide conservative estimates of the air quality impact of a specific source, or source category. These are called screening techniques or screening models. The purpose of such techniques is to eliminate the need of more detailed modeling for those sources that clearly will not cause or contribute to ambient concentrations in excess of either the National Ambient Air Quality Standards (NAAQS)[4] or the allowable prevention of significant deterioration (PSD) concentration increments.[2 3] If a screening technique indicates that the concentration contributed by the source exceeds the PSD increment or the increment remaining to just meet the NAAQS, then the second level of more sophisticated models should be applied.

b. The second level consists of those analytical techniques that provide more detailed treatment of physical and chemical atmospheric processes, require more detailed and precise input data, and provide more specialized concentration estimates. As a result they provide a more refined and, at least theoretically, a more accurate estimate of source impact and the effectiveness of control strategies. These are referred to as refined models.

c. The use of screening techniques followed, as appropriate, by a more refined analysis is always desirable. However there are situations where the screening techniques are practically and technically the only viable option for estimating source impact. In such cases, an attempt should be made to acquire or improve the necessary data bases and to develop appropriate analytical techniques.

2.3 Availability of Models

a. For most of the screening and refined models discussed in the *Guideline*, codes, associated documentation and other useful information are available for download from EPA's Support Center for Regulatory Air Modeling (SCRAM) Internet Web site at *http://www.epa.gov/scram001*. A list of alternate models that can be used with case-by-case justification (subsection 3.2) and an example air quality analysis checklist are also posted on this Web site. This is a site with which modelers should become familiar.

3.0 Recommended Air Quality Models

a. This section recommends the approach to be taken in determining refined modeling techniques for use in regulatory air quality programs. The status of models developed by EPA, as well as those submitted to EPA for review and possible inclusion in this guidance, is discussed. The section also addresses the selection of models for individual cases and provides recommendations for situations where the preferred models are not applicable. Two additional sources of modeling guidance are the Model Clearinghouse [5] and periodic Regional/State/Local Modelers workshops.

b. In this guidance, when approval is required for a particular modeling technique or analytical procedure, we often refer to the *''appropriate reviewing authority''*. In some EPA regions, authority for NSR and PSD permitting and related activities has been delegated to State and even local agencies. In these cases, such agencies are *''representatives''* of the respective regions. Even in these circumstances, the Regional Office retains the ultimate authority in decisions and approvals. Therefore, as discussed above and depending on the circumstances, the appropriate reviewing authority may be the Regional Office, Federal Land Manager(s), State agency(ies), or perhaps local agency(ies). In cases where review and approval comes solely from the Regional Office (sometimes stated as *''Regional Administrator''*), this will be stipulated. If there is any question as to the appropriate reviewing authority, you should contact the Regional modeling contact (*http://www.epa.gov/scram001/tt28.htm#regionalmodelingcontacts*) in the appropriate EPA Regional Office, whose jurisdiction generally includes the physical location of the source in question and its expected impacts.

c. In all regulatory analyses, especially if other-than-preferred models are selected for use, early discussions among Regional Office staff, State and local control agencies, industry representatives, and where appropriate, the Federal Land Manager, are invaluable and are encouraged. Agreement on the data base(s) to be used, modeling techniques to be applied and the overall technical approach, prior to the actual analyses, helps avoid misunderstandings concerning the final results and may reduce the later need for additional analyses. The use of an air quality analysis checklist, such as is posted on EPA's Internet SCRAM Web site (subsection 2.3), and the preparation of a written protocol help to keep misunderstandings at a minimum.

d. It should not be construed that the preferred models identified here are to be permanently used to the exclusion of all others or that they are the only models available for relating emissions to air quality. The model that most accurately estimates concentrations in the area of interest is always sought. However, designation of specific models is needed to promote consistency in model selection and application.

e. The 1980 solicitation of new or different models from the technical community [6] and the program whereby these models were evaluated, established a means by which new models are identified, reviewed and made available in the *Guideline*. There is a pressing need for the development of models for a wide range of regulatory applications. Refined models that more realistically simulate the physical and chemical process in the atmosphere and that more reliably estimate pollutant concentrations are needed.

3.1 Preferred Modeling Techniques

3.1.1 Discussion

a. EPA has developed models suitable for regulatory application. Other models have been submitted by private developers for possible inclusion in the *Guideline*. Refined models which are preferred and recommended by EPA have undergone evaluation exercises [7 8 9 10] that include statistical measures of model performance in comparison with measured air quality data as suggested by the American Meteorological Society [11] and, where possible, peer scientific reviews.[12 13 14]

b. When a single model is found to perform better than others, it is recommended for application as a preferred model and listed in Appendix A. If no one model is found to clearly perform better through the evaluation exercise, then the preferred model listed in Appendix A may be selected on the basis of other factors such as past use, public familiarity, cost or resource requirements, and availability. Accordingly, dispersion models listed in Appendix A meet these conditions:

i. The model must be written in a common programming language, and the executable(s) must run on a common computer platform.

ii. The model must be documented in a user's guide which identifies the mathematics of the model, data requirements and program operating characteristics at a level of detail comparable to that available for other recommended models in Appendix A.

iii. The model must be accompanied by a complete test data set including input parameters and output results. The test data must be packaged with the model in computer-readable form.

iv. The model must be useful to typical users, e.g., State air pollution control agencies, for specific air quality control problems. Such users should be able to operate the computer program(s) from available documentation.

v. The model documentation must include a comparison with air quality data (and/or tracer measurements) or with other well-established analytical techniques.

vi. The developer must be willing to make the model and source code available to users at reasonable cost or make them available for public access through the Internet or National Technical Information Service: The model and its code cannot be proprietary.

c. The evaluation process includes a determination of technical merit, in accordance with the above six items including the practicality of the model for use in ongoing regulatory programs. Each model will also be subjected to a performance evaluation for an appropriate data base and to a peer scientific review. Models for wide use (not just an isolated case) that are found to perform better will be proposed for inclusion as preferred models in future *Guideline* revisions.

d. No further evaluation of a preferred model is required for a particular application if the EPA recommendations for regulatory use specified for the model in the *Guideline* are followed. Alternative models to those listed in Appendix A should generally be compared with measured air quality data when they are used for regulatory applications consistent with recommendations in subsection 3.2.

3.1.2 Recommendations

a. Appendix A identifies refined models that are preferred for use in regulatory applications. If a model is required for a particular application, the user should select a model from that appendix. These models may be used without a formal demonstration of applicability as long as they are used as indicated in each model summary of Appendix A. Further recommendations for the application of these models to specific source problems are found in subsequent sections of the *Guideline*.

b. If changes are made to a preferred model without affecting the concentration estimates, the preferred status of the model is unchanged. Examples of modifications that do not affect concentrations are those made to enable use of a different computer platform or those that affect only the format or averaging time of the model results. However, when any changes are made, the Regional Administrator should require a test case example to demonstrate that the concentration estimates are not affected.

c. A preferred model should be operated with the options listed in Appendix A as ''Recommendations for Regulatory Use.'' If other options are exercised, the model is no longer ''preferred.'' Any other modification to a preferred model that would result in a change in the concentration estimates likewise alters its status as a preferred model. Use of the model must then be justified on a case-by-case basis.

3.2 Use of Alternative Models

3.2.1 Discussion

a. Selection of the best techniques for each individual air quality analysis is always encouraged, but the selection should be done in a consistent manner. A simple listing of models in this *Guideline* cannot alone achieve that consistency nor can it necessarily provide the best model for all possible situations. An EPA reference [15] provides a statistical technique for evaluating model performance for predicting peak concentration values, as might be observed at individual monitoring locations. This protocol is available to assist in developing a consistent approach when justifying the use of other-than-preferred modeling techniques recommended in the *Guideline*. The procedures in this protocol provide a general framework for objective decision-making on the acceptability of an alternative model for a given regulatory application. These objective procedures may be used for conducting both the technical evaluation of the model and the field test or performance evaluation. An ASTM reference [16] provides a general philosophy for developing and implementing advanced statistical evaluations of atmospheric dispersion models, and provides an example statistical technique to illustrate the application of this philosophy.

b. This section discusses the use of alternate modeling techniques and defines three situations when alternative models may be used.

3.2.2 Recommendations

a. Determination of acceptability of a model is a Regional Office responsibility. Where the Regional Administrator finds that an alternative model is more appropriate than a preferred model, that model may be used subject to the recommendations of this subsection. This finding will normally result from a determination that (1) a preferred air quality model is not appropriate for the particular application; or (2) a more appropriate model or analytical procedure is available and applicable.

b. An alternative model should be evaluated from both a theoretical and a performance perspective before it is selected for use. There are three separate conditions under which such a model may normally be approved for use: (1) If a demonstration can be made that the model produces concentration estimates equivalent to the estimates obtained using a preferred model; (2) if a statistical performance evaluation has been conducted using measured air quality data and the results of that evaluation indicate the alternative model performs better for the given application than a comparable model in Appendix A; or (3) if the preferred model is less appropriate for the specific application, or there is no preferred model. Any one of these three separate conditions may make use of an alternative model acceptable. Some known alternative models that are applicable for selected situations are listed on EPA's SCRAM Internet Web site (subsection 2.3). However, inclusion there does not confer any unique status relative to other alternative models that are being or will be developed in the future.

c. Equivalency, condition (1) in paragraph (b) of this subsection, is established by demonstrating that the maximum or highest, second highest concentrations are within 2 percent of the estimates obtained from the preferred model. The option to show equivalency is intended as a simple demonstration of acceptability for an alternative model that is so nearly identical (or contains options that can make it identical) to a preferred model that it can be treated for practical purposes as the preferred model. Two percent was selected as the basis for equivalency since it is a rough approximation of the fraction that PSD Class I increments are of the NAAQS for SO_2, i.e., the difference in concentrations that is judged to be significant. However, notwithstanding this demonstration, models that are not equivalent may be used when one of the two other conditions described in paragraphs (d) and (e) of this subsection are satisfied.

d. For condition (2) in paragraph (b) of this subsection, established procedures and techniques [15 16] for determining the acceptability of a model for an individual case based on superior performance should be followed, as appropriate. Preparation and implementation of an evaluation protocol which is acceptable to both control agencies and regulated industry is an important element in such an evaluation.

e. Finally, for condition (3) in paragraph (b) of this subsection, an alternative refined model may be used provided that:

i. The model has received a scientific peer review;

ii. The model can be demonstrated to be applicable to the problem on a theoretical basis;

iii. The data bases which are necessary to perform the analysis are available and adequate;

iv. Appropriate performance evaluations of the model have shown that the model is not biased toward underestimates; and

v. A protocol on methods and procedures to be followed has been established.

3.3 Availability of Supplementary Modeling Guidance

a. The Regional Administrator has the authority to select models that are appropriate for use in a given situation. However, there is a need for assistance and guidance in the selection process so that fairness and consistency in modeling decisions is fostered among the various Regional Offices and the States. To satisfy that need, EPA established the Model Clearinghouse [5] and also holds periodic workshops with headquarters, Regional Office, State, and local agency modeling representatives.

b. The Regional Office should always be consulted for information and guidance concerning modeling methods and interpretations of modeling guidance, and to ensure that the air quality model user has available the latest most up-to-date policy and procedures. As appropriate, the Regional Office may request assistance from the Model Clearinghouse after an initial evaluation and decision has been reached concerning the application of a model, analytical technique or data base in a particular regulatory action.

4.0 Traditional Stationary Source Models

4.1 Discussion

a. Guidance in this section applies to modeling analyses for which the predominant meteorological conditions that control the design concentration are steady state and for which the transport distances are nominally 50km or less. The models recommended in this section are generally used in the air quality impact analysis of stationary sources for most criteria pollutants. The averaging time of the concentration estimates produced by these models ranges from 1 hour to an annual average.

b. Simple terrain, as used here, is considered to be an area where terrain features are all lower in elevation than the top of the stack of the source(s) in question. Complex terrain is defined as terrain exceeding the height of the stack being modeled.

c. In the early 1980s, model evaluation exercises were conducted to determine the ''best, most appropriate point source model'' for use in simple terrain.[12] No one model was found to be clearly superior and, based on past use, public familiarity, and availability, ISC (predecessor to ISC3 [17]) became the recommended model for a wide range of regulatory applications. Other refined models which also employed the same basic Gaussian kernel as in ISC, i.e., BLP, CALINE3 and OCD, were developed for specialized applications (Appendix A). Performance evaluations were also made for these models, which are identified below.

d. Encouraged by the development of pragmatic methods for better characterization of plume dispersion [18 19 20 21] the AMS/EPA Regulatory Model Improvement Committee (AERMIC) developed AERMOD.[22] AERMOD employs best state-of-practice parameterizations for characterizing the meteorological influences and dispersion. The model utilizes a probability density function (pdf) and the superposition of several Gaussian plumes to characterize the distinctly non-Gaussian nature of the vertical pollutant distribution for elevated plumes during convective conditions; otherwise the distribution is Gaussian. Also, nighttime urban boundary layers (and plumes within them) have the turbulence enhanced by AERMOD to simulate the influence of the urban heat island. AERMOD has been evaluated using a variety of data sets and has been found to perform better than ISC3 for many applications, and as well or better than CTDMPLUS for several complex terrain data sets (Section A.1; subsection n). The current version of AERMOD has been modified to include an algorithm for dry and wet deposition for both gases and particles. Note that when deposition is invoked, mass in the plume is depleted. Availability of this version is described in Section A.1, and is subject to applicable guidance published in the *Guideline*.

e. A new building downwash algorithm [23] was developed and tested within AERMOD. The PRIME algorithm has been evaluated using a variety of data sets and has been found to perform better than the downwash algorithm that is in ISC3, and has been shown to perform acceptably in tests within AERMOD (Section A.1; subsection n).

4.2 Recommendations

4.2.1 Screening Techniques

4.2.1.1 Simple Terrain

a. Where a preliminary or conservative estimate is desired, point source screening techniques are an acceptable approach to air quality analyses. EPA has published guidance for screening procedures.[24 25]

b. All screening procedures should be adjusted to the site and problem at hand. Close attention should be paid to whether the area should be classified urban or rural in accordance with Section 7.2.3. The climatology of the area should be studied to help define the worst-case meteorological conditions. Agreement should be reached between the model user and the appropriate reviewing authority on the choice of the screening model for each analysis, and on the input data as well as the ultimate use of the results.

4.2.1.2 Complex Terrain

a. CTSCREEN [26] can be used to obtain conservative, yet realistic, worst-case estimates for receptors located on terrain above stack height. CTSCREEN accounts for the three-dimensional nature of plume and terrain interaction and requires detailed terrain data representative of the modeling domain. The model description and user's instructions are contained in the user's guide.[26] The terrain data must be digitized in the same manner as for CTDMPLUS and a terrain processor is available.[27] A discussion of the model's performance characteristics is provided in a technical paper.[28] CTSCREEN is designed to execute a fixed matrix of meteorological values for wind speed (u), standard deviation of horizontal and vertical wind speeds (σ_v, σ_w), vertical potential temperature gradient (dθ/dz), friction velocity (u_*), Monin-Obukhov length (L), mixing height (z_i) as a function of terrain height, and wind directions for both neutral/stable conditions and unstable convective conditions. Table 4–1 contains the matrix of meteorological variables that is used for each CTSCREEN analysis. There are 96 combinations, including exceptions, for each wind direction for the neutral/stable case, and 108 combinations for the unstable case. The specification of wind direction, however, is handled internally, based on the source and terrain geometry. Although CTSCREEN is designed to address a single source scenario, there are a number of options that can be selected on a case-by-case basis to address multi-source situations. However, the appropriate reviewing authority should be consulted, and concurrence obtained, on the protocol for modeling multiple sources with CTSCREEN to ensure that the worst case is identified and assessed. The maximum concentration output from CTSCREEN represents a worst-case 1-hour concentration. Time-scaling factors of 0.7 for 3-hour, 0.15 for 24-hour and 0.03 for annual concentration averages are applied internally by CTSCREEN to the highest 1-hour concentration calculated by the model.

b. Placement of receptors requires very careful attention when modeling in complex terrain. Often the highest concentrations are predicted to occur under very stable conditions, when the plume is near, or impinges on, the terrain. The plume under such conditions may be quite narrow in the vertical, so that even relatively small changes in a receptor's location may substantially affect the predicted concentration. Receptors within about a kilometer of the source may be even more sensitive to location. Thus, a dense array of receptors may be required in some cases. In order to avoid excessively large computer runs due to such a large array of receptors, it is often desirable to model the area twice. The first model run would use a moderate number of receptors carefully located over the area of interest. The second model run would use a more dense array of receptors in areas showing potential for high concentrations, as indicated by the results of the first model run.

c. As mentioned above, digitized contour data must be preprocessed [27] to provide hill shape parameters in suitable input format. The user then supplies receptors either through an interactive program that is part of the model or directly, by using a text editor; using both methods to select receptors will generally be necessary to assure that the maximum concentrations are estimated by either model. In cases where a terrain feature may ''appear to the plume'' as smaller, multiple hills, it may be necessary to model the terrain both as a single feature and as multiple hills to determine design concentrations.

d. Other screening techniques [17 25 29] may be acceptable for complex terrain cases where established procedures are used. The user is encouraged to confer with the appropriate reviewing authority if any unresolvable problems are encountered, *e.g.*, applicability, meteorological data, receptor siting, or terrain contour processing issues.

4.2.2 Refined Analytical Techniques

a. A brief description of each preferred model for refined applications is found in Appendix A. Also listed in that appendix are availability, the model input requirements, the standard options that should be selected when running the program, and output options.

b. For a wide range of regulatory applications in all types of terrain, the recommended model is AERMOD. This recommendation is based on extensive developmental and performance evaluation (Section A.1; subsection n). Differentiation of simple versus complex terrain is unnecessary with AERMOD. In complex terrain, AERMOD employs the well-known dividing-streamline concept in a simplified simulation of the effects of plume-terrain interactions.

c. If aerodynamic building downwash is important for the modeling analysis, *e.g.*, paragraph 6.2.2(b), then the recommended model is AERMOD. The state-of-the-science for modeling atmospheric deposition is evolving and the best techniques are currently being assessed and their results are being compared with observations. Consequently, while deposition treatment is available in AERMOD, the approach taken for any purpose should be coordinated with the appropriate reviewing authority. Line sources can be simulated with AERMOD if point or volume sources are appropriately combined. If buoyant plume rise from line sources is important for the modeling analysis, the recommended model is BLP. For other special modeling applications, CALINE3 (or CAL3QHCR on a case-by-case basis), OCD, and EDMS are available as described in Sections 5 and 6.

d. If the modeling application involves a well defined hill or ridge and a detailed dispersion analysis of the spatial pattern of plume impacts is of interest, CTDMPLUS, listed in Appendix A, is available. CDTMPLUS provides greater resolution of concentrations about the contour of the hill feature than does AERMOD through a different plume-terrain interaction algorithm.

TABLE 4–1A.—NEUTRAL/STABLE METEOROLOGICAL MATRIX FOR CTSCREEN

Variable	Specific values				
U (m/s)	1.0	2.0	3.0	4.0	5.0
σ_v (m/s)	0.3	0.75			
σ_w (m/s)	0.08	0.15	0.30	0.75	
Δθ/Δz (K/m)	0.01	0.02	0.035		
WD	(Wind direction is optimized internally for each meteorological combination.)				

Exceptions:

(1) If $U \leq 2$ m/s and $\sigma_v \leq 0.3$ m/s, then include $\sigma_w = 0.04$ m/s.

(2) If $\sigma_w = 0.75$ m/s and $U \geq 3.0$ m/s, then $\Delta\theta/\Delta z$ is limited to ≤ 0.01 K/m.

(3) If $U \geq 4$ m/s, then $\sigma_w \geq 0.15$ m/s.

(4) $\sigma_w \leq \sigma_v$

TABLE 4–1B.—UNSTABLE/CONVECTIVE METEOROLOGICAL MATRIX FOR CTSCREEN

Variable	Specific values				
U (m/s)	1.0	2.0	3.0	4.0	5.0
U_* (m/s)	0.1	0.3	0.5		
L (m)	−10	−50	−90		
$\Delta\theta/\Delta z$ (K/m)	0.030	(potential temperature gradient above Z_i)			
Z_i (m)	0.5h	1.0h	1.5h	(h = terrain height)	

5.0 Models for Ozone, Particulate Matter, Carbon Monoxide, Nitrogen Dioxide, and Lead

5.1 Discussion

a. This section identifies modeling approaches or models appropriate for addressing ozone (O_3)[a], carbon monoxide (CO), nitrogen dioxide (NO_2), particulates (PM–2.5[a] and PM–10), and lead. These pollutants are often associated with emissions from numerous sources. Generally, mobile sources contribute significantly to emissions of these pollutants or their precursors. For cases where it is of interest to estimate concentrations of CO or NO_2 near a single or small group of stationary sources, refer to Section 4. (Modeling approaches for SO_2 are discussed in Section 4.)

b. Several of the pollutants mentioned in the preceding paragraph are closely related to each other in that they share common sources of emissions and/or are subject to chemical transformations of similar precursors.[30 31] For example, strategies designed to reduce ozone could have an effect on the secondary component of PM–2.5 and vice versa. Thus, it makes sense to use models which take into account the chemical coupling between O_3 and PM–2.5, when feasible. This should promote consistency among methods used to evaluate strategies for reducing different pollutants as well as consistency among the strategies themselves. Regulatory requirements for the different pollutants are likely to be due at different times. Thus, the following paragraphs identify appropriate modeling approaches for pollutants individually.

c. The NAAQS for ozone was revised on July 18, 1997 and is now based on an 8-hour averaging period. Models for ozone are needed primarily to guide choice of strategies to correct an observed ozone problem in an area not attaining the NAAQS for ozone. Use of photochemical grid models is the recommended means for identifying strategies needed to correct high ozone concentrations in such areas. Such models need to consider emissions of volatile organic compounds (VOC), nitrogen oxides (NO_X) and carbon monoxide (CO), as well as means for generating meteorological data governing transport and dispersion of ozone and its precursors. Other approaches, such as Lagrangian or observational models may be used to guide choice of appropriate strategies to consider with a photochemical grid model. These other approaches may be sufficient to address ozone in an area where observed concentrations are near the NAAQS or only slightly above it. Such a decision needs to be made on a case-by-case basis in concert with the Regional Office.

d. A control agency with jurisdiction over one or more areas with significant ozone problems should review available ambient air quality data to assess whether the problem is likely to be significantly impacted by regional transport.[32] Choice of a modeling approach depends on the outcome of this review. In cases where transport is considered significant, use of a nested regional model may be the preferred approach. If the observed problem is believed to be primarily of local origin, use of a model with a single horizontal grid resolution and geographical coverage that is less than that of a regional model may suffice.

e. The fine particulate matter NAAQS, promulgated on July 18, 1997, includes particles with an aerodynamic diameter nominally less than or equal to 2.5 micrometers (PM–2.5). Models for PM–2.5 are needed to assess adequacy of a proposed strategy for meeting annual and/or 24-hour NAAQS for PM–2.5. PM–2.5 is a mixture consisting of several diverse components. Because chemical/physical properties and origins of each component differ, it may be appropriate to use either a single model capable of addressing several of the important components or to model primary and secondary components using different models. Effects of a control strategy on PM–2.5 is estimated from the sum of the effects on the components composing PM–2.5. Model users may refer to guidance[33] for further details concerning appropriate modeling approaches.

f. A control agency with jurisdiction over one or more areas with PM–2.5 problems should review available ambient air quality data to assess which components of PM–2.5 are likely to be major contributors to the problem. If it is determined that regional transport of secondary particulates, such as sulfates or nitrates, is likely to contribute significantly to the problem, use of a regional model may be the preferred approach. Otherwise, coverage may be limited to a domain that is urban scale or less. Special care should be taken to select appropriate geographical coverage for a modeling application.[33]

g. The NAAQS for PM–10 was promulgated in July 1987 (40 CFR 50.6). A SIP development guide[34] is available to assist in PM–10 analyses and control strategy development. EPA promulgated regulations for PSD increments measured as PM–10 in a notice published on June 3, 1993 (40 CFR 51.166(c)). As an aid to assessing the impact on ambient air quality of particulate matter generated from prescribed burning activities, a reference[35] is available.

h. Models for assessing the impacts of particulate matter may involve dispersion models or receptor models, or a combination (depending on the circumstances). Receptor models focus on the behavior of the ambient environment at the point of impact as opposed to source-oriented dispersion models, which focus on the transport, diffusion, and transformation that begin at the source and continue to the receptor site. Receptor models attempt to identify and apportion sources by relating known sample compositions at receptors to measured or inferred compositions of source emissions. When complete and accurate emission inventories or meteorological characterization are unavailable, or unknown pollutant sources exist, receptor modeling may be necessary.

i. Models for assessing the impact of CO emissions are needed for a number of different purposes. Examples include evaluating effects of point sources, congested intersections and highways, as well as the cumulative effect of numerous sources of CO in an urban area.

j. Models for assessing the impact of sources on ambient NO_2 concentrations are primarily needed to meet new source review requirements, such as addressing the effect of a proposed source on PSD increments for annual concentrations of NO_2. Impact of an individual source on ambient NO_2 depends, in part, on the chemical environment into which the source's plume is to be emitted. There are several approaches for estimating effects of an individual source on ambient NO_2. One approach is through use of a plume-in-grid algorithm imbedded within a photochemical grid model. However, because of the rigor and complexity involved, and because this approach may not be capable of defining sub-grid concentration gradients, the plume-in-grid approach may be impractical for estimating effects on an annual PSD increment. A second approach which does not have this limitation and accommodates

[a] Modeling for attainment demonstrations for O_3 and PM–2.5 should be conducted in time to meet required SIP submission dates as provided for in the respective implementation rules. Information on implementation of the 8-hr O_3 and PM–2.5 standards is available at: *http://www.epa.gov/ttn/naags/.*

distance-dependent conversion ratios—the Plume Volume Molar Ratio Method (PVMRM) [36]—is currently being tested to determine suitability as a refined method. A third (screening) approach is to develop site specific (domain-wide) conversion factors based on measurements. If it is not possible to develop site specific conversion factors and use of the plume-in-grid algorithm is also not feasible, other screening procedures may be considered.

k. In January 1999 (40 CFR Part 58, Appendix D), EPA gave notice that concern about ambient lead impacts was being shifted away from roadways and toward a focus on stationary point sources. EPA has also issued guidance on siting ambient monitors in the vicinity of such sources.[37] For lead, the SIP should contain an air quality analysis to determine the maximum quarterly lead concentration resulting from major lead point sources, such as smelters, gasoline additive plants, etc. General guidance for lead SIP development is also available.[38]

5.2 Recommendations

5.2.1 Models for Ozone

a. *Choice of Models for Multi-source Applications.* Simulation of ozone formation and transport is a highly complex and resource intensive exercise. Control agencies with jurisdiction over areas with ozone problems are encouraged to use photochemical grid models, such as the Models-3/Community Multi-scale Air Quality (CMAQ) modeling system,[39] to evaluate the relationship between precursor species and ozone. Judgement on the suitability of a model for a given application should consider factors that include use of the model in an attainment test, development of emissions and meteorological inputs to the model and choice of episodes to model.[32] Similar models for the 8-hour NAAQS and for the 1-hour NAAQS are appropriate.

b. *Choice of Models to Complement Photochemical Grid Models.* As previously noted, observational models, Lagrangian models, or the refined version of the Ozone Isopleth Plotting Program (OZIPR) [40] may be used to help guide choice of strategies to simulate with a photochemical grid model and to corroborate results obtained with a grid model. Receptor models have also been used to apportion sources of ozone precursors (*e.g.*, VOC) in urban domains. EPA has issued guidance [32] in selecting appropriate techniques.

c. *Estimating the Impact of Individual Sources.* Choice of methods used to assess the impact of an individual source depends on the nature of the source and its emissions. Thus, model users should consult with the Regional Office to determine the most suitable approach on a case-by-case basis (subsection 3.2.2).

5.2.2 Models for Particulate Matter

5.2.2.1 PM–2.5

a. *Choice of Models for Multi-source Applications.* Simulation of phenomena resulting in high ambient PM–2.5 can be a multi-faceted and complex problem resulting from PM–2.5's existence as an aerosol mixture. Treating secondary components of PM–2.5, such as sulfates and nitrates, can be a highly complex and resource-intensive exercise. Control agencies with jurisdiction over areas with secondary PM–2.5 problems are encouraged to use models which integrate chemical and physical processes important in the formation, decay and transport of these species (*e.g.*, Models-3/CMAQ [38] or REMSAD [41]). Primary components can be simulated using less resource-intensive techniques. Suitability of a modeling approach or mix of modeling approaches for a given application requires technical judgement,[33] as well as professional experience in choice of models, use of the model(s) in an attainment test, development of emissions and meteorological inputs to the model and selection of days to model.

b. *Choice of Analysis Techniques to Complement Air Quality Simulation Models.* Receptor models may be used to corroborate predictions obtained with one or more air quality simulation models. They may also be potentially useful in helping to define specific source categories contributing to major components of PM–2.5.[33]

c. *Estimating the Impact of Individual Sources.* Choice of methods used to assess the impact of an individual source depends on the nature of the source and its emissions. Thus, model users should consult with the Regional Office to determine the most suitable approach on a case-by-case basis (subsection 3.2.2).

5.2.2.2 PM–10

a. Screening techniques like those identified in subsection 4.2.1 are applicable to PM–10. Conservative assumptions which do not allow removal or transformation are suggested for screening. Thus, it is recommended that subjectively determined values for ''half-life'' or pollutant decay not be used as a surrogate for particle removal. Proportional models (rollback/forward) may not be applied for screening analysis, unless such techniques are used in conjunction with receptor modeling.[34]

b. Refined models such as those discussed in subsection 4.2.2 are recommended for PM–10. However, where possible, particle size, gas-to-particle formation, and their effect on ambient concentrations may be considered. For point sources of small particles and for source-specific analyses of complicated sources, use the appropriate recommended steady-state plume dispersion model (subsection 4.2.2).

c. Receptor models have proven useful for helping validate emission inventories and for corroborating source-specific impacts estimated by dispersion models. The Chemical Mass Balance (CMB) model is useful for apportioning impacts from localized sources.[42 43 44] Other receptor models, *e.g.*, the Positive Matrix Factorization (PMF) model [45] and Unmix,[46] which don't share some of CMB's constraints, have also been applied. In regulatory applications, dispersion models have been used in conjunction with receptor models to attribute source (or source category) contributions. Guidance is available for PM–10 sampling and analysis applicable to receptor modeling.[47]

d. Under certain conditions, recommended dispersion models may not be reliable. In such circumstances, the modeling approach should be approved by the Regional Office on a case-by-case basis. Analyses involving model calculations for stagnation conditions should also be justified on a case-by-case basis (subsection 7.2.8).

e. Fugitive dust usually refers to dust put into the atmosphere by the wind blowing over plowed fields, dirt roads or desert or sandy areas with little or no vegetation. Reentrained dust is that which is put into the air by reason of vehicles driving over dirt roads (or dirty roads) and dusty areas. Such sources can be characterized as line, area or volume sources. Emission rates may be based on site specific data or values from the general literature. Fugitive emissions include the emissions resulting from the industrial process that are not captured and vented through a stack but may be released from various locations within the complex. In some unique cases a model developed specifically for the situation may be needed. Due to the difficult nature of characterizing and modeling fugitive dust and fugitive emissions, it is recommended that the proposed procedure be cleared by the Regional Office for each specific situation before the modeling exercise is begun.

5.2.3 Models for Carbon Monoxide

a. Guidance is available for analyzing CO impacts at roadway intersections.[48] The recommended screening model for such analyses is CAL3QHC.[49 50] This model combines CALINE3 (listed in Appendix A) with a traffic model to calculate delays and queues that occur at signalized intersections. The screening approach is described in reference 48; a refined approach may be considered on a case-by-case basis with CAL3QHCR.[51] The latest version of the MOBILE (mobile source emission factor) model should be used for emissions input to intersection models.

b. For analyses of highways characterized by uninterrupted traffic flows, CALINE3 is recommended, with emissions input from the latest version of the MOBILE model. A scientific review article for line source models is available.[52]

c. For urban area wide analyses of CO, an Eulerian grid model should be used. Information on SIP development and requirements for using such models can be found in several references.[48 53 54 55]

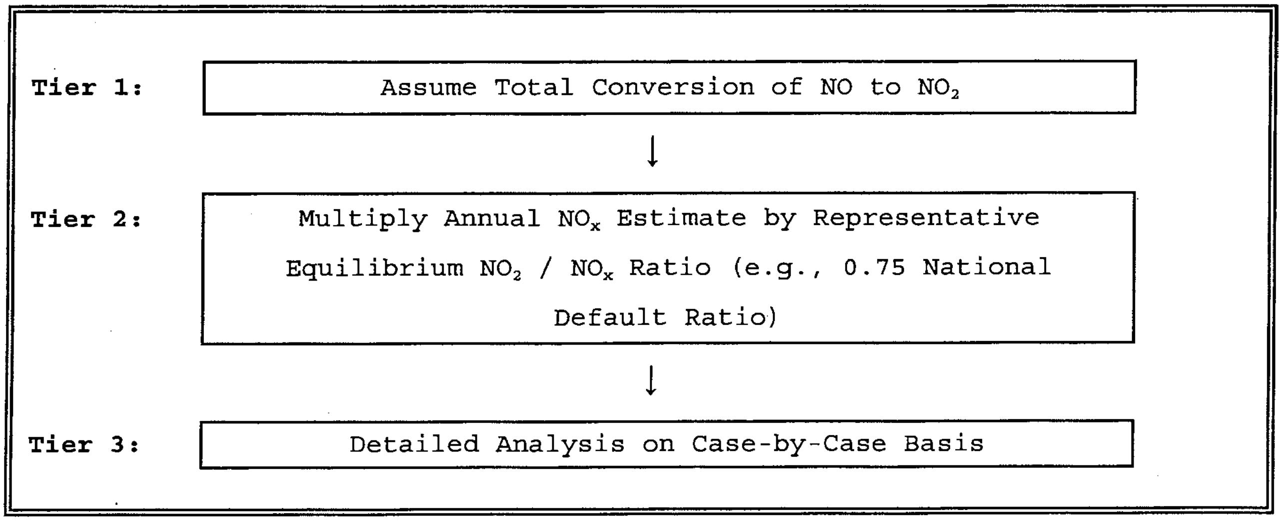
d. Where point sources of CO are of concern, they should be treated using the screening and refined techniques described in Section 4.

5.2.4 Models for Nitrogen Dioxide (Annual Average)

a. A tiered screening approach is recommended to obtain annual average estimates of NO_2 from point sources for New Source Review analysis, including PSD, and for SIP planning purposes. This multi-tiered approach is conceptually shown in Figure 5–1 and described in paragraphs b through d of this subsection:

Figure 5–1

Multi-tiered screening approach for Estimating Annual NO_2 Concentrations from Point Sources



b. For Tier 1 (the initial screen), use an appropriate model in subsection 4.2.2 to estimate the maximum annual average concentration and assume a total conversion of NO to NO_2. If the concentration exceeds the NAAQS and/or PSD increments for NO_2, proceed to the 2nd level screen.

c. For Tier 2 (2nd level) screening analysis, multiply the Tier 1 estimate(s) by an empirically derived NO_2/NO_X value of 0.75 (annual national default).[56] The reviewing agency may establish an alternative default NO_2/NO_X ratio based on ambient annual average NO_2 and annual average NO_X data representative of area wide quasi-equilibrium conditions. Alternative default NO_2/NO_X ratios should be based on data satisfying quality assurance procedures that ensure data accuracy for both NO_2 and NO_X within the typical range of measured values. In areas with relatively low NO_X concentrations, the quality assurance procedures used to determine compliance with the NO_2 national ambient air quality standard may not be adequate. In addition, default NO_2/NO_X ratios, including the 0.75 national default value, can underestimate long range NO_2 impacts and should be used with caution in long range transport scenarios.

d. For Tier 3 (3rd level) analysis, a detailed screening method may be selected on a case-by-case basis. For point source modeling, detailed screening techniques such as the Ozone Limiting Method[57] may also be considered. Also, a site specific NO_2/NO_X ratio may be used as a detailed screening method if it meets the same restrictions as described for alternative default NO_2/NO_X ratios. Ambient NO_X monitors used to develop a site specific ratio should be sited to obtain the NO_2 and NO_X concentrations under quasi-equilibrium conditions. Data obtained from monitors sited at the maximum NO_X impact site, as may be required in a PSD pre-construction monitoring program, likely reflect transitional NO_X conditions. Therefore, NO_X data from maximum impact sites may not be suitable for determining a site specific NO_2/NO_X ratio that is applicable for the entire modeling analysis. A site specific ratio derived from maximum impact data can only be used to estimate NO_2 impacts at receptors located within the same distance of the source as the source-to-monitor distance.

e. In urban areas (subsection 7.2.3), a proportional model may be used as a preliminary assessment to evaluate control strategies to meet the NAAQS for multiple minor sources, *i.e.*, minor point, area and mobile sources of NO_X; concentrations resulting from major point sources should be estimated separately as discussed above, then added to the impact of the minor sources. An acceptable screening technique for urban complexes is to assume that all NO_X is emitted in the form of NO_2 and to use a model from Appendix A for nonreactive pollutants to estimate NO_2 concentrations. A more accurate estimate can be obtained by: (1) Calculating the annual average concentrations of NO_X with an urban model, and (2) converting these estimates to NO_2 concentrations using an empirically derived annual NO_2/NO_X ratio. A value of 0.75 is recommended for this ratio. However, a spatially averaged alternative default annual NO_2/NO_X ratio may be determined from an existing air quality monitoring network and used in lieu of the 0.75 value if it is determined to be representative of prevailing ratios in the urban area by the reviewing agency. To ensure use of appropriate locally derived annual average NO_2/NO_X ratios, monitoring data under consideration should be limited to those collected at monitors meeting siting criteria defined in 40 CFR Part 58, Appendix D as representative of ''neighborhood'', ''urban'', or ''regional'' scales. Furthermore, the highest annual spatially averaged NO_2/NO_X ratio from the most recent 3 years of complete data should be used to foster conservatism in estimated impacts.

f. To demonstrate compliance with NO_2 PSD increments in urban areas, emissions from major and minor sources should be included in the modeling analysis. Point and area source emissions should be modeled as discussed above. If mobile source emissions do not contribute to localized areas of high ambient NO_2 concentrations, they should be modeled as area sources. When modeled as area sources, mobile source emissions should be assumed uniform over the entire highway link and allocated to each area source grid square based on the portion of highway link within each grid square. If localized areas of high concentrations are likely, then mobile sources should be modeled as line sources using an appropriate steady-state plume dispersion model (*e.g.*, CAL3QHCR; subsection 5.2.3).

g. More refined techniques to handle special circumstances may be considered on a case-by-case basis and agreement with the appropriate reviewing authority (paragraph 3.0(b)) should be obtained. Such techniques should consider individual quantities of NO and NO_2 emissions, atmospheric transport and dispersion, and atmospheric transformation of NO to NO_2. Where they are available, site specific data on the conversion of NO to NO_2 may be used. Photochemical dispersion models, if used for other pollutants in the area, may also be applied to the NO_X problem.

5.2.5 Models for Lead

a. For major lead point sources, such as smelters, which contribute fugitive emissions and for which deposition is important, professional judgement should be used, and there should be coordination with the appropriate reviewing authority (paragraph 3.0(b)). To model an entire major urban area or to model areas without significant sources of lead emissions, as a minimum a proportional (rollback) model may be used for air quality analysis. The rollback philosophy assumes that measured pollutant concentrations are proportional to emissions. However, urban or other dispersion models are encouraged in these circumstances where the use of such models is feasible.

b. In modeling the effect of traditional line sources (such as a specific roadway or highway) on lead air quality, dispersion models applied for other pollutants can be used. Dispersion models such as CALINE3 and CAL3QHCR have been used for modeling carbon monoxide emissions from highways and intersections (subsection 5.2.3). Where there is a point source in the middle of a substantial road network, the lead concentrations that result from the road network should be treated as background (subsection 8.2); the point source and any nearby major roadways should be modeled separately using the appropriate recommended steady-state plume dispersion model (subsection 4.2.2).

6.0 Other Model Requirements

6.1 Discussion

a. This section covers those cases where specific techniques have been developed for special regulatory programs. Most of the programs have, or will have when fully developed, separate guidance documents that cover the program and a discussion of the tools that are needed. The following paragraphs reference those guidance documents, when they are available. No attempt has been made to provide a comprehensive discussion of each topic since the reference documents were designed to do that. This section will undergo periodic revision as new programs are added and new techniques are developed.

b. Other Federal agencies have also developed specific modeling approaches for their own regulatory or other requirements.[58] Although such regulatory requirements and manuals may have come about because of EPA rules or standards, the implementation of such regulations and the use of the modeling techniques is under the jurisdiction of the agency issuing the manual or directive.

c. The need to estimate impacts at distances greater than 50km (the nominal distance to which EPA considers most steady-state Gaussian plume models are applicable) is an important one especially when considering the effects from secondary pollutants. Unfortunately, models originally available to EPA had not undergone sufficient field evaluation to be recommended for general use. Data bases from field studies at mesoscale and long range transport distances were limited in detail. This limitation was a result of the expense to perform the field studies required to verify and improve mesoscale and long range transport models. Meteorological data adequate for generating three-dimensional wind fields were particularly sparse. Application of models to complicated terrain compounds the difficulty of making good assessments of long range transport impacts. EPA completed limited evaluation of several long range transport (LRT) models against two sets of field data and evaluated results.[59] Based on the results, EPA concluded that long range and mesoscale transport models were limited for regulatory use to a case-by-case basis. However a more recent series of comparisons has been completed for a new model, CALPUFF (Section A.3). Several of these field studies involved three-to-four hour releases of tracer gas sampled along arcs of receptors at distances greater than 50km downwind. In some cases, short-term concentration sampling was available, such that the transport of the tracer puff as it passed the arc could be monitored. Differences on the order of 10 to 20 degrees were found between the location of the simulated and observed center of mass of the tracer puff. Most of the simulated centerline concentration maxima along each arc were within a factor of two of those observed. It was concluded from these case studies that the CALPUFF dispersion model had performed in a reasonable manner, and had no apparent bias toward over or under prediction, so long as the transport distance was limited to less than 300km.[60]

6.2 Recommendations

6.2.1 Visibility

a. Visibility in important natural areas (e.g., Federal Class I areas) is protected under a number of provisions of the Clean Air Act, including Sections 169A and 169B (addressing impacts primarily from existing sources) and Section 165 (new source review). Visibility impairment is caused by light scattering and light absorption associated with particles and gases in the atmosphere. In most areas of the country, light scattering by PM–2.5 is the most significant component of visibility impairment. The key components of PM–2.5 contributing to visibility impairment include sulfates, nitrates, organic carbon, elemental carbon, and crustal material.

b. The visibility regulations as promulgated in December 1980 (40 CFR 51.300–307) require States to mitigate visibility impairment, in any of the 156 mandatory Federal Class I areas, that is found to be ‘‘reasonably attributable’’ to a single source or a small group of sources. In 1985, EPA promulgated Federal Implementation Plans (FIPs) for several States without approved visibility provisions in their SIPs. The IMPROVE (Interagency Monitoring for Protected Visual Environments) monitoring network, a cooperative effort between EPA, the States, and Federal land management agencies, was established to implement the monitoring requirements in these FIPs. Data has been collected by the IMPROVE network since 1988.

c. In 1999, EPA issued revisions to the 1980 regulations to address visibility impairment in the form of regional haze, which is caused by numerous, diverse sources (e.g., stationary, mobile, and area sources) located across a broad region (40 CFR 51.308–309). The state of relevant scientific knowledge has expanded significantly since the Clean Air Act Amendments of 1977. A number of studies and reports [61 62] have concluded that long range transport (e.g., up to hundreds of kilometers) of fine particulate matter plays a significant role in visibility impairment across the country. Section 169A of the Act requires states to develop SIPs containing long-term strategies for remedying existing and preventing future visibility impairment in 156 mandatory Class I federal areas. In order to develop long-term strategies to address regional haze, many States will need to conduct regional-scale modeling of fine particulate concentrations and associated visibility impairment (e.g., light extinction and deciview metrics).

d. To calculate the potential impact of a plume of specified emissions for specific transport and dispersion conditions (‘‘plume blight’’), a screening model, VISCREEN, and guidance are available.[63] If a more comprehensive analysis is required, a refined model should be selected . The model selection (VISCREEN vs. PLUVUE II or some other refined model), procedures, and analyses should be determined in consultation with the appropriate reviewing authority (paragraph 3.0(b)) and the affected Federal Land Manager (FLM). FLMs are responsible for determining whether there is an adverse effect by a plume on a Class I area.

e. CALPUFF (Section A.3) may be applied when assessment is needed of reasonably attributable haze impairment or atmospheric deposition due to one or a small group of sources. This situation may involve more sources and larger modeling domains than that to which VISCREEN ideally may be applied. The procedures and analyses should be determined in consultation with the appropriate reviewing authority (paragraph 3.0(b)) and the affected FLM(s).

f. Regional scale models are used by EPA to develop and evaluate national policy and assist State and local control agencies. Two such models which can be used to assess visibility impacts from source emissions are Models-3/CMAQ [38] and REMSAD.[41] Model users should consult with the appropriate reviewing authority (paragraph 3.0(b)), which in this instance would include FLMs.

6.2.2 Good Engineering Practice Stack Height

a. The use of stack height credit in excess of Good Engineering Practice (GEP) stack height or credit resulting from any other dispersion technique is prohibited in the development of emission limitations by 40 CFR 51.118 and 40 CFR 51.164. The definitions of GEP stack height and dispersion technique are contained in 40 CFR 51.100. Methods and procedures for making the appropriate stack height calculations, determining stack height credits and an example of applying those techniques are found in several references [64 65 66 67], which provide a great deal of additional information for evaluating and describing building cavity and wake effects.

b. If stacks for new or existing major sources are found to be less than the height defined by EPA's refined formula for determining GEP height, then air quality impacts associated with cavity or wake effects due to the nearby building structures should be determined. The EPA refined formula height is defined as H + 1.5L (*see* reference 66). Detailed downwash screening procedures [24] for both the cavity and wake regions should be followed. If more refined concentration estimates are required, the recommended steady-state plume dispersion model in subsection 4.2.2 contains algorithms for building wake calculations and should be used.

6.2.3 Long Range Transport (LRT) (*i.e.,* Beyond 50km)

a. Section 165(d) of the Clean Air Act requires that suspected adverse impacts on PSD Class I areas be determined. However, 50km is the useful distance to which most steady-state Gaussian plume models are considered accurate for setting emission limits. Since in many cases PSD analyses show that Class I areas may be threatened at distances greater than 50km from new sources, some procedure is needed to (1) determine if an adverse impact will occur, and (2) identify the model to be used in setting an emission limit if the Class I increments are threatened. In addition to the situations just described, there are certain applications containing a mixture of both long range and short range source-receptor relationships in a large modeled domain (*e.g.,* several industrialized areas located along a river or valley). Historically, these applications have presented considerable difficulty to an analyst if impacts from sources having transport distances greater than 50km significantly contributed to the design concentrations. To properly analyze applications of this type, a modeling approach is needed which has the capability of combining, in a consistent manner, impacts involving both short and long range transport. The CALPUFF modeling system, listed in Appendix A, has been designed to accommodate both the Class I area LRT situation and the large modeling domain situation. Given the judgement and refinement involved, conducting a LRT modeling assessment will require significant consultation with the appropriate reviewing authority (paragraph 3.0(b)) and the affected FLM(s). The FLM has an affirmative responsibility to protect air quality related values (AQRVs) that may be affected, and to provide the appropriate procedures and analysis techniques. Where there is no increment violation, the ultimate decision on whether a Class I area is adversely affected is the responsibility of the appropriate reviewing authority (Section 165(d)(2)(C)(ii) of the Clean Air Act), taking into consideration any information on the impacts on AQRVs provided by the FLM. According to Section 165(d)(2)(C)(iii) of the Clean Air Act, if there is a Class I increment violation, the *source* must demonstrate to the satisfaction of the FLM that the emissions from the source will have no adverse impact on the AQRVs.

b. If LRT is determined to be important, then refined estimates utilizing the CALPUFF modeling system should be obtained. A screening approach [60 68] is also available for use on a case-by-case basis that generally provides concentrations that are higher than those obtained using refined characterizations of the meteorological conditions. The meteorological input data requirements for developing the time and space varying three-dimensional winds and dispersion meteorology for refined analyses are discussed in paragraph 8.3.1.2(d). Additional information on applying this model is contained in Appendix A. To facilitate use of complex air quality and meteorological modeling systems, a written protocol approved by the appropriate reviewing authority (paragraph 3.0(b)) and the affected FLM(s) may be considered for developing consensus in the methods and procedures to be followed.

6.2.4 Modeling Guidance for Other Governmental Programs

a. When using the models recommended or discussed in the *Guideline* in support of programmatic requirements not specifically covered by EPA regulations, the model user should consult the appropriate Federal or State agency to ensure the proper application and use of the models. For modeling associated with PSD permit applications that involve a Class I area, the appropriate Federal Land Manager should be consulted on all modeling questions.

b. The Offshore and Coastal Dispersion (OCD) model, described in Appendix A, was developed by the Minerals Management Service and is recommended for estimating air quality impact from offshore sources on onshore, flat terrain areas. The OCD model is not recommended for use in air quality impact assessments for onshore sources. Sources located on or just inland of a shoreline where fumigation is expected should be treated in accordance with subsection 7.2.8.

c. The latest version of the Emissions and Dispersion Modeling System (EDMS), was developed and is supported by the Federal Aviation Administration (FAA), and is appropriate for air quality assessment of primary pollutant impacts at airports or air bases. EDMS has adopted AERMOD for treating dispersion. Application of EDMS is intended for estimating the collective impact of changes in aircraft operations, point source, and mobile source emissions on pollutant concentrations. It is not intended for PSD, SIP, or other regulatory air quality analyses of point or mobile sources at or peripheral to airport property that are unrelated to airport operations. If changes in other than aircraft operations are associated with analyses, a model recommended in Chapter 4 or 5 should be used. The latest version of EDMS may be obtained from FAA at its Web site: *http://www.aee.faa.gov/emissions/edms/edmshome.htm.*

7.0 General Modeling Considerations

7.1 Discussion

a. This section contains recommendations concerning a number of different issues not explicitly covered in other sections of this guide. The topics covered here are not specific to any one program or modeling area but are common to nearly all modeling analyses for criteria pollutants.

7.2 Recommendations

7.2.1 Design Concentrations (*See Also* Subsection 10.2.3.1)

7.2.1.1 Design Concentrations for SO_2, PM–10, CO, Pb, and NO_2

a. An air quality analysis for SO_2, PM–10, CO, Pb, and NO_2 is required to determine if the source will (1) cause a violation of the NAAQS, or (2) cause or contribute to air quality deterioration greater than the specified allowable PSD increment. For the former, background concentration (subsection 8.2) should be added to the estimated impact of the source to determine the design concentration. For the latter, the design concentration includes impact from all increment consuming sources.

b. If the air quality analyses are conducted using the period of meteorological input data recommended in subsection 8.3.1.2 (*e.g.,* 5 years of National Weather Service (NWS) data or at least 1 year of site specific data; subsection 8.3.3), then the design concentration based on the highest, second-highest short term concentration over the entire receptor network for each year modeled or the highest long term average (whichever is controlling) should be used to determine emission limitations to assess compliance with the NAAQS and PSD increments. For the 24-hour PM–10 NAAQS (which is a probabilistic standard)—when multiple years are modeled, they collectively represent a single period. Thus, if 5 years of NWS data are modeled, then the highest sixth highest concentration for the whole period becomes the design value. And in general, when n years are modeled, the (n+1)th highest concentration over the n-year period is the design value, since this represents an average or expected exceedance rate of one per year.

c. When sufficient and representative data exist for less than a 5-year period from a nearby NWS site, or when site specific data have been collected for less than a full continuous year, or when it has been determined that the site specific data may not be temporally representative (subsection 8.3.3), then the highest concentration estimate should be considered the design value. This is because the length of the data record may be too short to assure that the conditions producing worst-case estimates have been adequately sampled. The highest value is then a surrogate for the concentration that is not to be exceeded more than once per year (the wording of the deterministic standards). Also, the highest concentration should be used whenever selected worst-case conditions are input to a screening technique, as described in EPA guidance.[24]

d. If the controlling concentration is an annual average value and multiple years of data (site specific or NWS) are used, then the design value is the highest of the annual averages calculated for the individual years. If the controlling concentration is a quarterly average and multiple years are used, then the highest individual quarterly average should be considered the design value.

e. As long a period of record as possible should be used in making estimates to determine design values and PSD increments. If more than 1 year of site specific data is available, it should be used.

7.2.1.2 Design Concentrations for O_3 and PM–2.5

a. Guidance and specific instructions for the determination of the 1-hr and 8-hr design concentrations for ozone are provided in Appendix H and I (respectively) of reference 4. Appendix H explains how to determine when the expected number of days per calendar year with maximum hourly concentrations above the NAAQS is equal to or less than 1. Appendix I explains the data handling conventions and computations necessary for determining whether the 8-hour primary and secondary NAAQS are met at an ambient monitoring site. For PM–2.5, Appendix N of reference 4, and supplementary guidance,[69] explain the data handling conventions and computations necessary for determining when the annual and 24-hour primary and secondary NAAQS are met. For all SIP revisions the user should check with the Regional Office to obtain the most recent guidance documents and policy memoranda concerning the pollutant in question. There are currently no PSD increments for O_3 and PM–2.5.

7.2.2 Critical Receptor Sites

a. Receptor sites for refined modeling should be utilized in sufficient detail to estimate the highest concentrations and possible violations of a NAAQS or a PSD increment. In designing a receptor network, the emphasis should be placed on receptor resolution and location, not total number of receptors. The selection of receptor sites should be a case-by-case determination taking into consideration the topography, the climatology, monitor sites, and the results of the initial screening procedure.

7.2.3 Dispersion Coefficients

a. Steady-state Gaussian plume models used in most applications should employ dispersion coefficients consistent with those contained in the preferred models in Appendix A. Factors such as averaging time, urban/rural surroundings (*see* paragraphs (b)—(f) of this subsection), and type of source (point vs. line) may dictate the selection of specific coefficients. Coefficients used in some Appendix A models are identical to, or at least based on, Pasquill-Gifford coefficients [70] in rural areas and McElroy-Pooler [71] coefficients in urban areas. A key feature of AERMOD's formulation is the use of directly observed variables of the boundary layer to parameterize dispersion.[22]

b. The selection of either rural or urban dispersion coefficients in a specific application should follow one of the procedures suggested by Irwin [72] and briefly described in paragraphs (c)—(f) of this subsection. These include a land use classification procedure or a population based procedure to determine whether the character of an area is primarily urban or rural.

c. Land Use Procedure: (1) Classify the land use within the total area, A_o, circumscribed by a 3km radius circle about the source using the meteorological land use typing scheme proposed by Auer [73]; (2) if land use types I1, I2, C1, R2, and R3 account for 50 percent or more of A_o, use urban dispersion coefficients; otherwise, use appropriate rural dispersion coefficients.

d. Population Density Procedure: (1) Compute the average population density, $\bar{p}$ per square kilometer with A_o as defined above; (2) If $\bar{p}$ is greater than 750 people/km_2, use urban dispersion coefficients; otherwise use appropriate rural dispersion coefficients.

e. Of the two methods, the land use procedure is considered more definitive. Population density should be used with caution and should not be applied to highly industrialized areas where the population density may be low and thus a rural classification would be indicated, but the area is sufficiently built-up so that the urban land use criteria would be satisfied. In this case, the classification should already be ''urban'' and urban dispersion parameters should be used.

f. Sources located in an area defined as urban should be modeled using urban dispersion parameters. Sources located in areas defined as rural should be modeled using the rural dispersion parameters. For analyses of whole urban complexes, the entire area should be modeled as an urban region if most of the sources are located in areas classified as urban.

g. Buoyancy-induced dispersion (BID), as identified by Pasquill [74], is included in the preferred models and should be used where buoyant sources, *e.g.*, those involving fuel combustion, are involved.

7.2.4 Stability Categories

a. The Pasquill approach to classifying stability is commonly used in preferred models (Appendix A). The Pasquill method, as modified by Turner [75], was developed for use with commonly observed meteorological data from the National Weather Service and is based on cloud cover, insolation and wind speed.

b. Procedures to determine Pasquill stability categories from other than NWS data are found in subsection 8.3. Any other method to determine Pasquill stability categories must be justified on a case-by-case basis.

c. For a given model application where stability categories are the basis for selecting dispersion coefficients, both σ_y and σ_z should be determined from the same stability category. ''Split sigmas'' in that instance are not recommended. Sector averaging, which eliminates the σ_y term, is commonly acceptable in complex terrain screening methods.

d. AERMOD, also a preferred model in Appendix A, uses a planetary boundary layer scaling parameter to characterize stability.[22] This approach represents a departure from the discrete, hourly stability categories estimated under the Pasquill-Gifford-Turner scheme.

7.2.5 Plume Rise

a. The plume rise methods of Briggs [76,77] are incorporated in many of the preferred models and are recommended for use in many modeling applications. In AERMOD,[22] for the stable boundary layer, plume rise is estimated using an iterative approach, similar to that in the CTDMPLUS model. In the convective boundary layer, plume rise is superposed on the displacements by random convective velocities.[78] In AERMOD, plume rise is computed using the methods of Briggs excepting cases involving building downwash, in which a numerical solution of the mass, energy, and momentum conservation laws is performed.[23] No explicit provisions in these models are made for multistack plume rise enhancement or the handling of such special plumes as flares; these problems should be considered on a case-by-case basis.

b. Gradual plume rise is generally recommended where its use is appropriate: (1) In AERMOD; (2) in complex terrain screening procedures to determine close-in impacts and (3) when calculating the effects of building wakes. The building wake algorithm in AERMOD incorporates and exercises the thermodynamically based gradual plume rise calculations as described in (a) above. If the building wake is calculated to affect the plume for any hour, gradual plume rise is also used in downwind dispersion calculations to the distance of final plume rise, after which final plume rise is used. Plumes captured by the near wake are re-emitted to the far wake as a ground-level volume source.

c. Stack tip downwash generally occurs with poorly constructed stacks and when the ratio of the stack exit velocity to wind speed is small. An algorithm developed by Briggs [77] is the recommended technique for this situation and is used in preferred models for point sources.

7.2.6 Chemical Transformation

a. The chemical transformation of SO_2 emitted from point sources or single industrial plants in rural areas is generally assumed to be relatively unimportant to the estimation of maximum concentrations when travel time is limited to a few hours. However, in urban areas, where synergistic effects among pollutants are of considerable consequence, chemical transformation rates may be of concern. In urban area applications, a half-life of 4 hours [75] may be applied to the analysis of SO_2 emissions. Calculations of transformation coefficients from site specific studies can be used to define a ''half-life'' to be used in a steady-state Gaussian plume model with any travel time, or in any application, if appropriate documentation is provided. Such conversion factors for pollutant half-life should not be used with screening analyses.

b. Use of models incorporating complex chemical mechanisms should be considered only on a case-by-case basis with proper demonstration of applicability. These are generally regional models not designed for the evaluation of individual sources but used primarily for region-wide evaluations. Visibility models also incorporate chemical transformation mechanisms which are an integral part of the visibility model itself and should be used in visibility assessments.

7.2.7 Gravitational Settling and Deposition

a. An ''infinite half-life'' should be used for estimates of particle concentrations when steady-state Gaussian plume models containing only exponential decay terms for treating settling and deposition are used.

b. Gravitational settling and deposition may be directly included in a model if either is a significant factor. When particulate matter sources can be quantified and settling and dry deposition are problems, professional judgement should be used, and there should be coordination with the appropriate reviewing authority (paragraph 3.0(b)).

7.2.8 Complex Winds

a. *Inhomogeneous Local Winds.* In many parts of the United States, the ground is neither flat nor is the ground cover (or land use) uniform. These geographical variations can generate local winds and circulations, and modify the prevailing ambient winds and circulations. Geographic effects are most apparent when the ambient winds are light or calm.[79] In general these geographically induced wind circulation effects are named after the source location of the winds, *e.g.*, lake and sea breezes, and mountain and valley winds. In very rugged hilly or mountainous terrain, along coastlines, or near large land use variations, the characterization of the winds is a balance of various forces, such that the assumptions of steady-state straight-line transport both in time and space are inappropriate. In the special cases described, the CALPUFF modeling system (described in Appendix A) may be applied on a case-by-case basis for air quality estimates in such complex non-steady-state meteorological conditions. The purpose of choosing a modeling system like CALPUFF is to fully treat the time and space variations of meteorology effects on transport and dispersion. The setup and application of the model should be determined in consultation with the appropriate reviewing authority (paragraph 3.0(b)) consistent with limitations of paragraph 3.2.2(e). The meteorological input data requirements for developing the time and space varying three-dimensional winds and dispersion meteorology for these situations are discussed in paragraphs 8.3.1.2(d) and 8.3.1.2(f). Examples of inhomogeneous winds include, but aren't limited to, situations described in the following paragraphs (i)—(iii):

i. *Inversion Breakup Fumigation.* Inversion breakup fumigation occurs when a plume (or multiple plumes) is emitted into a stable layer of air and that layer is subsequently mixed to the ground through convective transfer of heat from the surface or because of advection to less stable surroundings. Fumigation may cause excessively high concentrations but is usually rather short-lived at a given receptor. There are no recommended refined techniques to model this phenomenon. There are, however, screening procedures [24] that may be used to approximate the concentrations. Considerable care should be exercised in using the results obtained from the screening techniques.

ii. *Shoreline Fumigation.* Fumigation can be an important phenomenon on and near the shoreline of bodies of water. This can affect both individual plumes and area-wide emissions. When fumigation conditions are expected to occur from a source or sources with tall stacks located on or just inland of a shoreline, this should be addressed in the air quality modeling analysis. The Shoreline Dispersion Model (SDM) listed on EPA's Internet SCRAM Web site (subsection 2.3) may be applied on a case-by-case basis when air quality estimates under shoreline fumigation conditions are needed.[80] Information on the results of EPA's evaluation of this model together with other coastal fumigation models is available.[81] Selection of the appropriate model for applications where shoreline fumigation is of concern should be determined in consultation with the appropriate reviewing authority (paragraph 3.0(b)).

iii. *Stagnation.* Stagnation conditions are characterized by calm or very low wind speeds, and variable wind directions. These stagnant meteorological conditions may persist for several hours to several days. During stagnation conditions, the dispersion of air pollutants, especially those from low-level emissions sources, tends to be minimized, potentially leading to relatively high ground-level concentrations. If point sources are of interest, users should note the guidance provided for CALPUFF in paragraph (a) of this subsection. Selection of the appropriate model for applications where stagnation is of concern should be determined in consultation with the appropriate reviewing authority (paragraph 3.0(b)).

7.2.9 Calibration of Models

a. Calibration of models is not common practice and is subject to much error and misunderstanding. There have been attempts by some to compare model estimates and measurements on an event-by-event basis and then to calibrate a model with results of that comparison. This approach is severely limited by uncertainties in both source and meteorological data and therefore it is difficult to precisely estimate the concentration at an exact location for a specific increment of time. Such uncertainties make calibration of models of questionable benefit. Therefore, model calibration is unacceptable.

8.0 Model Input Data

a. Data bases and related procedures for estimating input parameters are an integral part of the modeling procedure. The most appropriate data available should always be selected for use in modeling analyses. Concentrations can vary widely depending on the source data or meteorological data used. Input data are a major source of uncertainties in any modeling analysis. This section attempts to minimize the uncertainty associated with data base selection and use by identifying requirements for data used in modeling. A checklist of input data requirements for modeling analyses is posted on EPA's Internet SCRAM Web site (subsection 2.3). More specific data requirements and the format required for the individual models are described in detail in the users' guide for each model.

8.1 Source Data

8.1.1 Discussion

a. Sources of pollutants can be classified as point, line and area/volume sources. Point sources are defined in terms of size and may vary between regulatory programs. The line sources most frequently considered are roadways and streets along which there are well-defined movements of motor vehicles, but they may be lines of roof vents or stacks such as in aluminum refineries. Area and volume sources are often collections of a multitude of minor sources with individually small emissions that are impractical to consider as separate point or line sources. Large area sources are typically treated as a grid network of square areas, with pollutant emissions distributed uniformly within each grid square.

b. Emission factors are compiled in an EPA publication commonly known as AP–42 [82]; an indication of the quality and amount of data on which many of the factors are based is also provided. Other information concerning emissions is available in EPA publications relating to specific source categories. The appropriate reviewing authority (paragraph 3.0(b)) should be consulted to determine appropriate source definitions and for guidance concerning the determination of emissions from and techniques for modeling the various source types.

8.1.2 Recommendations

a. For point source applications the load or operating condition that causes maximum ground-level concentrations should be established. As a minimum, the source should be modeled using the design capacity (100 percent load). If a source operates at greater than design capacity for periods that could result in violations of the standards or PSD increments, this load) [a] should be modeled. Where the source operates at substantially less than design capacity, and the changes in the stack parameters associated with the operating conditions could lead to higher ground level concentrations, loads such as 50 percent and 75 percent of capacity should also be modeled. A range of operating conditions should be considered in screening analyses; the load causing the highest concentration, in addition to the design load, should be included in refined modeling. For a steam power plant, the following (b–h) is typical of the kind of data on source characteristics and operating conditions that may be needed. Generally, input data requirements for air quality models necessitate the use of metric units; where English units are common for engineering usage, a conversion to metric is required.

b. *Plant layout.* The connection scheme between boilers and stacks, and the distance and direction between stacks, building parameters (length, width, height, location and orientation relative to stacks) for plant structures which house boilers, control equipment, and surrounding buildings within a distance of approximately five stack heights.

c. *Stack parameters.* For all stacks, the stack height and inside diameter (meters), and the temperature (K) and volume flow rate (actual cubic meters per second) or exit gas velocity (meters per second) for operation at 100 percent, 75 percent and 50 percent load.

d. *Boiler size.* For all boilers, the associated megawatts, 10^6 BTU/hr, and pounds of steam per hour, and the design and/or actual fuel consumption rate for 100 percent load for coal (tons/hour), oil (barrels/hour), and natural gas (thousand cubic feet/hour).

e. *Boiler parameters.* For all boilers, the percent excess air used, the boiler type (e.g., wet bottom, cyclone, etc.), and the type of firing (e.g., pulverized coal, front firing, etc.).

f. *Operating conditions.* For all boilers, the type, amount and pollutant contents of fuel, the total hours of boiler operation and the boiler capacity factor during the year, and the percent load for peak conditions.

g. *Pollution control equipment parameters.* For each boiler served and each pollutant affected, the type of emission control equipment, the year of its installation, its design efficiency and mass emission rate, the date of the last test and the tested efficiency, the number of hours of operation during the latest year, and the best engineering estimate of its projected efficiency if used in conjunction with coal combustion; data for any anticipated modifications or additions.

h. *Data for new boilers or stacks.* For all new boilers and stacks under construction

[a] Malfunctions which may result in excess emissions are not considered to be a normal operating condition. They generally should not be considered in determining allowable emissions. However, if the excess emissions are the result of poor maintenance, careless operation, or other preventable conditions, it may be necessary to consider them in determining source impact.

and for all planned modifications to existing boilers or stacks, the scheduled date of completion, and the data or best estimates available for items (b) through (g) of this subsection following completion of construction or modification.

i. In stationary point source applications for compliance with short term ambient standards, SIP control strategies should be tested using the emission input shown on Table 8–1. When using a refined model, sources should be modeled sequentially with these loads for every hour of the year. To evaluate SIPs for compliance with quarterly and annual standards, emission input data shown in Table 8–1 should again be used. Emissions from area sources should generally be based on annual average conditions. The source input information in each model user's guide should be carefully consulted and the checklist (paragraph 8.0(a)) should also be consulted for other possible emission data that could be helpful. NAAQS compliance demonstrations in a PSD analysis should follow the emission input data shown in Table 8–2. For purposes of emissions trading, new source review and demonstrations, refer to current EPA policy and guidance to establish input data.

j. Line source modeling of streets and highways requires data on the width of the roadway and the median strip, the types and amounts of pollutant emissions, the number of lanes, the emissions from each lane and the height of emissions. The location of the ends of the straight roadway segments should be specified by appropriate grid coordinates. Detailed information and data requirements for modeling mobile sources of pollution are provided in the user's manuals for each of the models applicable to mobile sources.

k. The impact of growth on emissions should be considered in all modeling analyses covering existing sources. Increases in emissions due to planned expansion or planned fuel switches should be identified. Increases in emissions at individual sources that may be associated with a general industrial/commercial/residential expansion in multi-source urban areas should also be treated. For new sources the impact of growth on emissions should generally be considered for the period prior to the start-up date for the source. Such changes in emissions should treat increased area source emissions, changes in existing point source emissions which were not subject to preconstruction review, and emissions due to sources with permits to construct that have not yet started operation.

TABLE 8–1.—MODEL EMISSION INPUT DATA FOR POINT SOURCES [1]

Averaging time	Emission limit (#/MMBtu) [2]	×	Operating level (MMBtu/hr) [2]	×	Operating factor (e.g., hr/yr, hr/day)
Stationary Point Source(s) Subject to SIP Emission Limit(s) Evaluation for Compliance with Ambient Standards (Including Areawide Demonstrations)					
Annual & quarterly	Maximum allowable emission limit or federally enforceable permit limit.		Actual or design capacity (whichever is greater), or federally enforceable permit condition.		Actual operating factor averaged over most recent 2 years.[3]
Short term	Maximum allowable emission limit or federally enforceable permit limit.		Actual or design capacity (whichever is greater), or federally enforceable permit condition.[4]		Continuous operation, i.e., all hours of each time period under consideration (for all hours of the meteorological data base).[5]
Nearby Source(s) [6 7] Same input requirements as for stationary point source(s) above.					
Other Source(s) [7] If modeled (subsection 8.2.3), input data requirements are defined below.					
Annual & quarterly	Maximum allowable emission limit or federally enforceable permit limit.[6]		Annual level when actually operating, averaged over the most recent 2 years.[3]		Actual operating factor averaged over the most recent 2 years.[3]
Short term	Maximum allowable emission limit or federally enforceable permit limit.[6]		Annual level when actually operating, averaged over the most recent 2 years.[3]		Continuous operation, i.e., all hours of each time period under consideration (for all hours of the meteorological data base).[5]

[1] The model input data requirements shown on this table apply to stationary source control strategies for STATE IMPLEMENTATION PLANS. For purposes of emissions trading, new source review, or prevention of significant deterioration, other model input criteria may apply. Refer to the policy and guidance for these programs to establish the input data.

[2] Terminology applicable to fuel burning sources; analogous terminology (e.g., #/throughput) may be used for other types of sources.

[3] Unless it is determined that this period is not representative.

[4] Operating levels such as 50 percent and 75 percent of capacity should also be modeled to determine the load causing the highest concentration.

[5] If operation does not occur for all hours of the time period of consideration (e.g., 3 or 24 hours) and the source operation is constrained by a federally enforceable permit condition, an appropriate adjustment to the modeled emission rate may be made (e.g., if operation is only 8 a.m. to 4 p.m. each day, only these hours will be modeled with emissions from the source. Modeled emissions should not be averaged across non-operating time periods.)

[6] See paragraph 8.2.3(c).

[7] See paragraph 8.2.3(d).

TABLE 8–2.—POINT SOURCE MODEL EMISSION INPUT DATA FOR NAAQS COMPLIANCE IN PSD DEMONSTRATIONS

Averaging time	Emission limit (#/MMBtu)[1]	×	Operating level (MMBtu/hr)[1]	×	Operating factor (e.g., hr/yr, hr/day)
Proposed Major New or Modified Source					
Annual & quarterly	Maximum allowable emission limit or federally enforceable permit limit.		Design capacity or federally enforceable permit condition.		Continuous operation (i.e., 8760 hours).[2]
Short term (≤ 24 hours)	Maximum allowable emission limit or federally enforceable permit limit.		Design capacity or federally enforceable permit condition.[3]		Continuous operation, i.e., all hours of each time period under consideration (for all hours of the meteorological data base).[2]
Nearby Source(s)[4 6]					
Annual & quarterly	Maximum allowable emission limit or federally enforceable permit limit.[5]		Actual or design capacity (whichever is greater), or federally enforceable permit condition.		Actual operating factor averaged over the most recent 2 years.[7 8]
Short term (≤ 24 hours)	Maximum allowable emission limit or federally enforceable permit limit.[5]		Actual or design capacity (whichever is greater), or federally enforceable permit condition.[3]		Continuous operation, i.e., all hours of each time period under consideration (for all hours of the meteorological data base).[2]
Other Source(s)[6 9]					
Annual & quarterly	Maximum allowable emission limit or federally enforceable permit limit.[5]		Annual level when actually operating, averaged over the most recent 2 years.[7]		Actual operating factor averaged over the most recent 2 years.[7 8]
Short term (≤ 24 hours)	Maximum allowable emission limit or federally enforceable permit limit.[5]		Annual level when actually operating, averaged over the most recent 2 years.[7]		Continuous operation, i.e., all hours of each time period under consideration (for all hours of the meteorological data base).[2]

[1] Terminology applicable to fuel burning sources; analogous terminology (e.g., #/throughput) may be used for other types of sources.
[2] If operation does not occur for all hours of the time period of consideration (e.g., 3 or 24 hours) and the source operation is constrained by a federally enforceable permit condition, an appropriate adjustment to the modeled emission rate may be made (e.g., if operation is only 8 a.m. to 4 p.m. each day, only these hours will be modeled with emissions from the source. Modeled emissions should not be averaged across non-operating time periods.
[3] Operating levels such as 50 percent and 75 percent of capacity should also be modeled to determine the load causing the highest concentration.
[4] Includes existing facility to which modification is proposed if the emissions from the existing facility will not be affected by the modification. Otherwise use the same parameters as for major modification.
[5] See paragraph 8.2.3(c).
[6] See paragraph 8.2.3(d).
[7] Unless it is determined that this period is not representative.
[8] For those permitted sources not in operation or that have not established an appropriate factor, continuous operation (i.e., 8760) should be used.
[9] Generally, the ambient impacts from non-nearby (background) sources can be represented by air quality data unless adequate data do not exist.

8.2 Background Concentrations

8.2.1 Discussion

a. Background concentrations are an essential part of the total air quality concentration to be considered in determining source impacts. Background air quality includes pollutant concentrations due to: (1) Natural sources; (2) nearby sources other than the one(s) currently under consideration; and (3) unidentified sources.

b. Typically, air quality data should be used to establish background concentrations in the vicinity of the source(s) under consideration. The monitoring network used for background determinations should conform to the same quality assurance and other requirements as those networks established for PSD purposes.[83] An appropriate data validation procedure should be applied to the data prior to use.

c. If the source is not isolated, it may be necessary to use a multi-source model to establish the impact of nearby sources. Since sources don't typically operate at their maximum allowable capacity (which may include the use of ''dirtier'' fuels), modeling is necessary to express the potential contribution of background sources, and this impact would not be captured via monitoring. Background concentrations should be determined for each critical (concentration) averaging time.

8.2.2 Recommendations (Isolated Single Source)

a. Two options (paragraph (b) or (c) of this section) are available to determine the background concentration near isolated sources.

b. Use air quality data collected in the vicinity of the source to determine the background concentration for the averaging times of concern. Determine the mean background concentration at each monitor by excluding values when the source in question is impacting the monitor. The mean annual background is the average of the annual concentrations so determined at each monitor. For shorter averaging periods, the meteorological conditions accompanying the concentrations of concern should be identified. Concentrations for meteorological conditions of concern, at monitors not impacted by the source in question, should be averaged for each separate averaging time to determine the average background value. Monitoring sites inside a 90° sector downwind of the source may be used to determine the area of impact. One hour concentrations may be added and averaged to determine longer averaging periods.

c. If there are no monitors located in the vicinity of the source, a ''regional site'' may be used to determine background. A ''regional site'' is one that is located away from the area of interest but is impacted by similar natural and distant man-made sources.

8.2.3 Recommendations (Multi-Source Areas)

a. In multi-source areas, two components of background should be determined: contributions from nearby sources and contributions from other sources.

b. *Nearby Sources:* All sources expected to cause a significant concentration gradient in the vicinity of the source or sources under consideration for emission limit(s) should be explicitly modeled. The number of such sources is expected to be small except in unusual situations. Owing to both the uniqueness of each modeling situation and the large number of variables involved in identifying nearby sources, no attempt is made here to comprehensively define this term. Rather, identification of nearby sources calls for the exercise of professional judgement by the appropriate reviewing authority (paragraph 3.0(b)). This guidance is not intended to alter the exercise of that judgement or to comprehensively define which sources are nearby sources.

c. For compliance with the short-term and annual ambient standards, the nearby sources as well as the primary source(s) should be evaluated using an appropriate Appendix A model with the emission input data shown in Table 8–1 or 8–2. When modeling a nearby source that does not have a permit and the emission limit contained in the SIP for a particular source category is greater than the emissions possible given the source's maximum physical capacity to emit, the ''maximum allowable emission limit'' for such a nearby source may be calculated as the emission rate representative of the nearby source's maximum physical capacity to emit, considering its design specifications and allowable fuels and process materials. However, the burden is on the permit applicant to sufficiently document what the maximum physical capacity to emit is for such a nearby source.

d. It is appropriate to model nearby sources only during those times when they, by their nature, operate at the same time as the primary source(s) being modeled. Where a primary source believes that a nearby source does not, by its nature, operate at the same time as the primary source being modeled, the burden is on the primary source to demonstrate to the satisfaction of the appropriate reviewing authority (paragraph 3.0(b)) that this is, in fact, the case. Whether or not the primary source has adequately demonstrated that fact is a matter of professional judgement left to the discretion of the appropriate reviewing authority. The following examples illustrate two cases in which a nearby source may be shown not to operate at the same time as the primary source(s) being modeled. Some sources are only used during certain seasons of the year. Those sources would not be modeled as nearby sources during times in which they do not operate. Similarly, emergency backup generators that never operate simultaneously with the sources that they back up would not be modeled as nearby sources. To reiterate, in these examples and other appropriate cases, the burden is on the primary source being modeled to make the appropriate demonstration to the satisfaction of the appropriate reviewing authority.

e. The impact of the nearby sources should be examined at locations where interactions between the plume of the point source under consideration and those of nearby sources (plus natural background) can occur. Significant locations include: (1) the area of maximum impact of the point source; (2) the area of maximum impact of nearby sources; and (3) the area where all sources combine to cause maximum impact. These locations may be identified through trial and error analyses.

f. *Other Sources:* That portion of the background attributable to all other sources (*e.g.*, natural sources, minor sources and distant major sources) should be determined by the procedures found in subsection 89.2.2 or by application of a model using Table 8–1 or 8–2.

8.3 Meteorological Input Data

a. The meteorological data used as input to a dispersion model should be selected on the basis of spatial and climatological (temporal) representativeness as well as the ability of the individual parameters selected to characterize the transport and dispersion conditions in the area of concern. The representativeness of the data is dependent on: (1) The proximity of the meteorological monitoring site to the area under consideration; (2) the complexity of the terrain; (3) the exposure of the meteorological monitoring site; and (4) the period of time during which data are collected. The spatial representativeness of the data can be adversely affected by large distances between the source and receptors of interest and the complex topographic characteristics of the area. Temporal representativeness is a function of the year-to-year variations in weather conditions. Where appropriate, data representativeness should be viewed in terms of the appropriateness of the data for constructing realistic boundary layer profiles and three dimensional meteorological fields, as described in paragraphs (c) and (d) below.

b. Model input data are normally obtained either from the National Weather Service or as part of a site specific measurement program. Local universities, Federal Aviation Administration (FAA), military stations, industry and pollution control agencies may also be sources of such data. Some recommendations for the use of each type of data are included in this subsection.

c. Regulatory application of AERMOD requires careful consideration of minimum data for input to AERMET. Data representativeness, in the case of AERMOD, means utilizing data of an appropriate type for constructing realistic boundary layer profiles. Of paramount importance is the requirement that all meteorological data used as input to AERMOD must be both laterally and vertically representative of the transport and dispersion within the analysis domain. Where surface conditions vary significantly over the analysis domain, the emphasis in assessing representativeness should be given to adequate characterization of transport and dispersion between the source(s) of concern and areas where maximum design concentrations are anticipated to occur. The representativeness of data that were collected off-site should be judged, in part, by comparing the surface characteristics in the vicinity of the meteorological monitoring site with the surface characteristics that generally describe the analysis domain. The surface characteristics input to AERMET should be based on the topographic conditions in the vicinity of the meteorological tower. Furthermore, since the spatial scope of each variable could be different, representativeness should be judged for each variable separately. For example, for a variable such as wind direction, the data may need to be collected very near plume height to be adequately representative, whereas, for a variable such as temperature, data from a station several kilometers away from the source may in some cases be considered to be adequately representative.

d. For long range transport modeling assessments (subsection 6.2.3) or for assessments where the transport winds are complex and the application involves a non-steady-state dispersion model (subsection 7.2.8), use of output from prognostic mesoscale meteorological models is encouraged.[84 85 86] Some diagnostic meteorological processors are designed to appropriately blend available NWS comparable meteorological observations, local site specific meteorological observations, and prognostic mesoscale meteorological data, using empirical relationships, to diagnostically adjust the wind field for mesoscale and local-scale effects. These diagnostic adjustments can sometimes be improved through the use of strategically placed site specific meteorological observations. The placement of these special meteorological observations (often more than one location is needed) involves expert judgement, and is specific to the terrain and land use of the modeling domain. Acceptance for use of output from prognostic mesoscale meteorological models is contingent on concurrence by the appropriate reviewing authorities (paragraph 3.0(b)) that the data are of acceptable quality, which can be demonstrated through statistical comparisons with observations of winds aloft and at the surface at several appropriate locations.

8.3.1 Length of Record of Meteorological Data

8.3.1.1 Discussion

a. The model user should acquire enough meteorological data to ensure that worst-case meteorological conditions are adequately represented in the model results. The trend toward statistically based standards suggests a need for all meteorological conditions to be adequately represented in the data set selected for model input. The number of years of record needed to obtain a stable distribution of conditions depends on the variable being measured and has been estimated by Landsberg and Jacobs [87] for various parameters. Although that study indicates in excess of 10 years may be required to achieve stability in the frequency distributions of some meteorological variables, such long periods are not reasonable for model input data. This is due in part to the fact that hourly data in model input format are frequently not available for such periods and that hourly calculations of concentration for long periods may be prohibitively expensive. Another study [88] compared various periods from a 17-year data set to determine the minimum number of years of data needed to approximate the concentrations modeled with a 17-year period of meteorological data from one station. This study indicated that the variability of model estimates due to the meteorological data input was adequately reduced if a 5-year period of record of meteorological input was used.

8.3.1.2 Recommendations

a. Five years of representative meteorological data should be used when estimating concentrations with an air quality model. Consecutive years from the most recent, readily available 5-year period are preferred. The meteorological data should be *adequately representative*, and may be site specific or from a nearby NWS station. Where professional judgment indicates NWS-collected ASOS (automated surface observing stations) data are inadequate {for cloud cover observations}, the most recent 5 years of NWS data that are observer-based may be considered for use.

b. The use of 5 years of NWS meteorological data or at least l year of site specific data is required. If one year or more (including partial years), up to five years, of site specific data is available, these data are preferred for use in air quality analyses. Such data should have been subjected to quality assurance procedures as described in subsection 8.3.3.2.

c. For permitted sources whose emission limitations are based on a specific year of meteorological data, that year should be added to any longer period being used (*e.g.*, 5 years of NWS data) when modeling the facility at a later time.

d. For LRT situations (subsection 6.2.3) and for complex wind situations (paragraph 7.2.8(a)), if only NWS or comparable standard meteorological observations are employed, five years of meteorological data (within and near the modeling domain) should be used. Consecutive years from the most recent, readily available 5-year period are preferred. Less than five, but at least three, years of meteorological data (need not be consecutive) may be used if mesoscale meteorological fields are available, as discussed in paragraph 8.3(d). These mesoscale meteorological fields should be used in conjunction with available standard NWS or comparable meteorological observations within and near the modeling domain.

e. For solely LRT applications (subsection 6.2.3), if site specific meteorological data are available, these data may be helpful when used in conjunction with available standard NWS or comparable observations and mesoscale meteorological fields as described in paragraph 8.3.1.2(d).

f. For complex wind situations (paragraph 7.2.8(a)) where site specific meteorological data are being relied upon as the basis for characterizing the meteorological conditions, a data base of at least 1 full-year of meteorological data is required. If more data are available, they should be used. Site specific meteorological data may have to be collected at multiple locations. Such data should have been subjected to quality assurance procedures as described in paragraph 8.3.3.2(a), and should be reviewed for spatial and temporal representativeness.

8.3.2 National Weather Service Data

8.3.2.1 Discussion

a. The NWS meteorological data are routinely available and familiar to most model users. Although the NWS does not provide direct measurements of all the needed dispersion model input variables, methods have been developed and successfully used to translate the basic NWS data to the needed model input. Site specific measurements of model input parameters have been made for many modeling studies, and those methods and techniques are becoming more widely applied, especially in situations such as complex terrain applications, where available NWS data are not adequately representative. However, there are many model applications where NWS data are adequately representative, and the applications still rely heavily on the NWS data.

b. Many models use the standard hourly weather observations available from the National Climatic Data Center (NCDC). These observations are then preprocessed before they can be used in the models.

8.3.2.2 Recommendations

a. The preferred models listed in Appendix A all accept as input the NWS meteorological data preprocessed into model compatible form. If NWS data are judged to be adequately representative for a particular modeling application, they may be used. NCDC makes available surface [89 90] and upper air [91] meteorological data in CD–ROM format.

b. Although most NWS measurements are made at a standard height of 10 meters, the actual anemometer height should be used as input to the preferred model. Note that AERMOD at a minimum requires wind observations at a height above ground between seven times the local surface roughness height and 100 meters.

c. Wind directions observed by the National Weather Service are reported to the nearest 10 degrees. A specific set of randomly generated numbers has been developed for use with the preferred EPA models and should be used with NWS data to ensure a lack of bias in wind direction assignments within the models.

d. Data from universities, FAA, military stations, industry and pollution control agencies may be used if such data are equivalent in accuracy and detail to the NWS data, and they are judged to be adequately representative for the particular application.

8.3.3 Site Specific Data

8.3.3.1 Discussion

a. Spatial or geographical representativeness is best achieved by collection of all of the needed model input data in close proximity to the actual site of the source(s). Site specific measured data are therefore preferred as model input, provided that appropriate instrumentation and quality assurance procedures are followed and that the data collected are adequately representative (free from inappropriate local or microscale influences) and compatible with the input requirements of the model to be used. It should be noted that, while site specific measurements are frequently made ''on-property'' (*i.e.*, on the source's premises), acquisition of adequately representative site specific data does not preclude collection of data from a location off property. Conversely, collection of meteorological data on a source's property does not of itself guarantee adequate representativeness. For help in determining representativeness of site specific measurements, technical guidance [92] is available. Site specific data should always be reviewed for representativeness and consistency by a qualified meteorologist.

8.3.3.2 Recommendations

a. EPA guidance [92] provides recommendations on the collection and use of site specific meteorological data. Recommendations on characteristics, siting, and exposure of meteorological instruments and on data recording, processing, completeness requirements, reporting, and archiving are also included. This publication should be used as a supplement to other limited guidance on these subjects.[83 93 94] Detailed information on quality assurance is also available.[95] As a minimum, site specific measurements of ambient air temperature, transport wind speed and direction, and the variables necessary to estimate atmospheric dispersion should be available in meteorological data sets to be used in modeling. Care should be taken to ensure that meteorological instruments are located to provide representative characterization of pollutant transport between sources and receptors of interest. The appropriate reviewing authority (paragraph 3.0(b)) is available to help determine the appropriateness of the measurement locations.

b. All site specific data should be reduced to hourly averages. Table 8–3 lists the wind related parameters and the averaging time requirements.

c. *Missing Data Substitution.* After valid data retrieval requirements have been met [92], hours in the record having missing data should be treated according to an established data substitution protocol provided that data from an adequately representative alternative site are available. Such protocols are usually part of the approved monitoring program plan. Data substitution guidance is provided in Section 5.3 of reference 92. If no representative alternative data are available for substitution, the absent data should be coded as missing using missing data codes appropriate to the applicable meteorological pre-processor. Appropriate model options for treating missing data, if available in the model, should be employed.

d. *Solar Radiation Measurements.* Total solar radiation or net radiation should be measured with a reliable pyranometer or net radiometer, sited and operated in accordance with established site specific meteorological guidance.[92 95]

e. *Temperature Measurements.* Temperature measurements should be made at standard shelter height (2m) in accordance with established site specific meteorological guidance.[92]

f. *Temperature Difference Measurements.* Temperature difference (ΔT) measurements should be obtained using matched thermometers or a reliable thermocouple system to achieve adequate accuracy. Siting, probe placement, and operation of ΔT systems should be based on guidance found in Chapter 3 of reference 92, and such guidance should be followed when obtaining vertical temperature gradient data. AERMET employs the Bulk Richardson scheme which requires measurements of temperature difference. To ensure correct application and acceptance, AERMOD users should consult with the appropriate Reviewing Authority before using the Bulk Richardson scheme for their analysis.

g. *Winds Aloft.* For simulation of plume rise and dispersion of a plume emitted from a stack, characterization of the wind profile up through the layer in which the plume disperses is required. This is especially important in complex terrain and/or complex wind situations where wind measurements at heights up to hundreds of meters above stack base may be required in some circumstances. For tall stacks when site specific data are needed, these winds have been obtained traditionally using meteorological sensors mounted on tall towers. A feasible alternative to tall towers is the use of meteorological remote sensing instruments (e.g., acoustic sounders or radar wind profilers) to provide winds aloft, coupled with 10-meter towers to provide the near-surface winds. (For specific requirements for AERMOD and CTDMPLUS, *see* Appendix A.) Specifications for wind measuring instruments and systems are contained in reference 92.

h. *Turbulence.* There are several dispersion models that are capable of using direct measurements of turbulence (wind fluctuations) in the characterization of the vertical and lateral dispersion (e.g., CTDMPLUS, AERMOD, and CALPUFF). For specific requirements for CTDMPLUS, AERMOD, and CALPUFF, see Appendix A. For technical guidance on measurement and processing of turbulence parameters, see reference 92. When turbulence data are used in this manner to directly characterize the vertical and lateral dispersion, the averaging time for the turbulence measurements should be one hour (Table 8–3). There are other dispersion models (e.g., BLP, and CALINE3) that employ P–G stability categories for the characterization of the vertical and lateral dispersion. Methods for using site specific turbulence data for the characterization of P–G stability categories are discussed in reference 92. When turbulence data are used in this manner to determine the P–G stability category, the averaging time for the turbulence measurements should be 15 minutes.

i. *Stability Categories.* For dispersion models that employ P–G stability categories for the characterization of the vertical and lateral dispersion, the P–G stability categories, as originally defined, couple near-surface measurements of wind speed with subjectively determined insolation assessments based on hourly cloud cover and ceiling height observations. The wind speed measurements are made at or near 10m. The insolation rate is typically assessed using observations of cloud cover and ceiling height based on criteria outlined by Turner.[70] It is recommended that the P–G stability category be estimated using the Turner method with site specific wind speed measured at or near 10m and representative cloud cover and ceiling height. Implementation of the Turner method, as well as considerations in determining representativeness of cloud cover and ceiling height in cases for which site specific cloud observations are unavailable, may be found in Section 6 of reference 92. In the absence of requisite data to implement the Turner method, the SRDT method or wind fluctuation statistics (i.e., the σ_E and σ_A methods) may be used.

j. The SRDT method, described in Section 6.4.4.2 of reference 92, is modified slightly from that published from earlier work[96] and has been evaluated with three site specific data bases.[97] The two methods of stability classification which use wind fluctuation statistics, the σ_E and σ_A methods, are also described in detail in Section 6.4.4 of reference 92 (note applicable tables in Section 6). For additional information on the wind fluctuation methods, several references are available.[98 99 100 101]

k. *Meteorological Data Preprocessors.* The following meteorological preprocessors are recommended by EPA: AERMET,[102] PCRAMMET,[103] MPRM,[104] METPRO,[105] and CALMET[106] AERMET, which is patterned after MPRM, should be used to preprocess all data for use with AERMOD. Except for applications that employ AERMOD, PCRAMMET is the recommended meteorological preprocessor for use in applications employing hourly NWS data. MPRM is a general purpose meteorological data preprocessor which supports regulatory models requiring PCRAMMET formatted (NWS) data. MPRM is available for use in applications employing site specific meteorological data. The latest version (MPRM 1.3) has been configured to implement the SRDT method for estimating P–G stability categories. METPRO is the required meteorological data preprocessor for use with CTDMPLUS. CALMET is available for use with applications of CALPUFF. All of the above mentioned data preprocessors are available for downloading from EPA's Internet SCRAM Web site (subsection 2.3).

TABLE 8–3.—AVERAGING TIMES FOR SITE SPECIFIC WIND AND TURBULENCE MEASUREMENTS

Parameter	Averaging time (hour)
Surface wind speed (for use in stability determinations)	1
Transport direction	1
Dilution wind speed	1
Turbulence measurements (σ_E and σ_A) for use in stability determinations	1[1]
Turbulence measurements for direct input to dispersion models	1

[1] To minimize meander effects in σ_A when wind conditions are light and/or variable, determine the hourly average σ value from four sequential 15-minute σ's according to the following formula:

$$\sigma_{1-hr} = \sqrt{\frac{\sigma_{15}^2 + \sigma_{15}^2 + \sigma_{15}^2 + \sigma_{15}^2}{4}}$$

8.3.4 Treatment of Near-Calms and Calms

8.3.4.1 Discussion

a. Treatment of calm or light and variable wind poses a special problem in model applications since steady-state Gaussian plume models assume that concentration is inversely proportional to wind speed. Furthermore, concentrations may become unrealistically large when wind speeds less than 1 m/s are input to the model. Procedures have been developed to prevent the occurrence of overly conservative concentration estimates during periods of calms. These procedures acknowledge that a steady-state Gaussian plume model does not apply during calm conditions, and that our knowledge of wind patterns and plume behavior during these conditions does not, at present, permit the development of a better technique. Therefore, the procedures disregard hours which are identified as calm. The hour is treated as missing and a convention for handling missing hours is recommended.

b. AERMOD, while fundamentally a steady-state Gaussian plume model, contains algorithms for dealing with low wind speed (near calm) conditions. As a result, AERMOD can produce model estimates for conditions when the wind speed may be less than 1 m/s, but still greater than the instrument threshold. Required input to AERMET, the meteorological processor for AERMOD, includes a threshold wind speed and a reference wind speed. The threshold wind speed is typically the threshold of the instrument used to collect the wind speed data. The reference wind speed is selected by the model as the lowest level of non-missing wind speed and direction data where the speed is greater than the wind speed threshold, and the height of the measurement is between seven times the local surface roughness and 100 meters. If the only valid observation of the reference wind speed between these heights is less than the threshold, the hour is considered calm, and no concentration is calculated. None of the observed wind speeds in a measured wind profile that are less than the threshold speed are used in construction of the modeled wind speed profile in AERMOD.

8.3.4.2 Recommendations

a. Hourly concentrations calculated with steady-state Gaussian plume models using calms should not be considered valid; the wind and concentration estimates for these hours should be disregarded and considered to be missing. Critical concentrations for 3-, 8-, and 24-hour averages should be calculated by dividing the sum of the hourly concentrations for the period by the number of valid or non-missing hours. If the total number of valid hours is less than 18 for 24-hour averages, less than 6 for 8-hour averages or less than 3 for 3-hour averages, the total concentration should be divided by 18 for the 24-hour average, 6 for the 8-hour average and 3 for the 3-hour average. For annual averages, the sum of all valid hourly concentrations is divided by the number of non-calm hours during the year. AERMOD has been coded to implement these instructions. For models listed in Appendix A, a post-processor computer program, CALMPRO [107] has been prepared, is available on the SCRAM Internet Web site (subsection 2.3), and should be used.

b. Stagnant conditions that include extended periods of calms often produce high concentrations over wide areas for relatively long averaging periods. The standard steady-state Gaussian plume models are often not applicable to such situations. When stagnation conditions are of concern, other modeling techniques should be considered on a case-by-case basis (see also subsection 7.2.8).

c. When used in steady-state Gaussian plume models, measured site specific wind speeds of less than 1 m/s but higher than the response threshold of the instrument should be input as 1 m/s; the corresponding wind direction should also be input. Wind observations below the response threshold of the instrument should be set to zero, with the input file in ASCII format. For input to AERMOD, no adjustment should be made to the site specific wind data. In all cases involving steady-state Gaussian plume models, calm hours should be treated as missing, and concentrations should be calculated as in paragraph (a) of this subsection.

9.0 Accuracy and Uncertainty of Models

9.1 Discussion

a. Increasing reliance has been placed on concentration estimates from models as the primary basis for regulatory decisions concerning source permits and emission control requirements. In many situations, such as review of a proposed source, no practical alternative exists. Therefore, there is an obvious need to know how accurate models really are and how any uncertainty in the estimates affects regulatory decisions. During the 1980's, attempts were made to encourage development of standardized evaluation methods.[11 108] EPA recognized the need for incorporating such information and has sponsored workshops [109] on model accuracy, the possible ways to quantify accuracy, and on considerations in the incorporation of model accuracy and uncertainty in the regulatory process. The Second (EPA) Conference on Air Quality Modeling, August 1982 [110], was devoted to that subject.

b. To better deduce the statistical significance of differences seen in model performance in the face of unaccounted for uncertainties and variations, investigators have more recently explored the use of bootstrap techniques.[111 112] Work is underway to develop a new generation of evaluation metrics [16] that takes into account the statistical differences (in error distributions) between model predictions and observations.[113] Even though the procedures and measures are still evolving to describe performance of models that characterize atmospheric fate, transport and diffusion [114 115 116], there has been general acceptance of a need to address the uncertainties inherent in atmospheric processes.

9.1.1 Overview of Model Uncertainty

a. Dispersion models generally attempt to estimate concentrations at specific sites that really represent an ensemble average of numerous repetitions of the same event.[16] The event is characterized by measured or ''known'' conditions that are input to the models, *e.g.,* wind speed, mixed layer height, surface heat flux, emission characteristics, etc. However, in addition to the known conditions, there are unmeasured or unknown variations in the conditions of this event, *e.g.,* unresolved details of the atmospheric flow such as the turbulent velocity field. These unknown conditions, may vary among repetitions of the event. As a result, deviations in observed concentrations from their ensemble average, and from the concentrations estimated by the model, are likely to occur even though the known conditions are fixed. Even with a *perfect model* that predicts the correct ensemble average, there are likely to be deviations from the observed concentrations in individual repetitions of the event, due to variations in the unknown conditions. The statistics of these concentration residuals are termed ''inherent'' uncertainty. Available evidence suggests that this source of uncertainty alone may be responsible for a typical range of variation in concentrations of as much as ±50 percent.[117]

b. Moreover, there is ''reducible'' uncertainty [108] associated with the model and its input conditions; neither models nor data bases are perfect. Reducible uncertainties are caused by: (1) Uncertainties in the input values of the known conditions (*i.e.,* emission characteristics and meteorological data); (2) errors in the measured concentrations which are used to compute the concentration residuals; and (3) inadequate model physics and formulation. The ''reducible'' uncertainties can be minimized through better (more accurate and more representative) measurements and better model physics.

c. To use the terminology correctly, reference to model accuracy should be limited to that portion of reducible uncertainty which deals with the physics and the formulation of the model. The accuracy of the model is normally determined by an evaluation procedure which involves the comparison of model concentration estimates with measured air quality data.[118] The statement of accuracy is based on statistical tests or performance measures such as bias, noise, correlation, etc.[11] However, information that allows a distinction between contributions of the various elements of inherent and reducible uncertainty is only now beginning to emerge.[16] As a result most discussions of the accuracy of models make no quantitative distinction between (1) limitations of the model versus (2) limitations of the data base and of knowledge concerning atmospheric variability. The reader should be aware that statements on model accuracy and uncertainty may imply the need for improvements in model performance that even the ''perfect'' model could not satisfy.

9.1.2 Studies of Model Accuracy

a. A number of studies [119 120] have been conducted to examine model accuracy, particularly with respect to the reliability of short-term concentrations required for ambient standard and increment evaluations. The results of these studies are not surprising. Basically, they confirm what expert atmospheric scientists have said for some time: (1) Models are more reliable for estimating longer time-averaged concentrations than for estimating short-term concentrations at specific locations; and (2) the models are reasonably reliable in estimating the magnitude of highest concentrations occurring sometime, somewhere within an area. For example, errors in highest estimated concentrations of ± 10 to 40 percent are found to be typical [121 122], *i.e.,* certainly well within the often quoted factor-of-two accuracy that has long been recognized for these models. However, estimates of concentrations that occur at a specific time and site, are poorly correlated with actually observed concentrations and are much less reliable.

b. As noted above, poor correlations between paired concentrations at fixed stations may be due to ''reducible'' uncertainties in knowledge of the precise plume location and to unquantified inherent uncertainties. For example, Pasquill [123] estimates that, apart from data input errors, maximum ground-level concentrations at a given hour for a point source in flat terrain could be in error by 50 percent due to these uncertainties. Uncertainty of five to 10 degrees in the measured wind direction, which transports the plume, can result in concentration errors of 20 to 70 percent for a particular time and location, depending on stability and station location. Such uncertainties do not indicate that an estimated concentration does not occur, only that the precise time and locations are in doubt.

9.1.3 Use of Uncertainty in Decision-Making

a. The accuracy of model estimates varies with the model used, the type of application, and site specific characteristics. Thus, it is desirable to quantify the accuracy or uncertainty associated with concentration estimates used in decision-making. Communications between modelers and decision-makers must be fostered and further developed. Communications concerning concentration estimates currently exist in most cases, but the communications dealing with the accuracy of models and its meaning to the decision-maker are limited by the lack of a technical basis for quantifying and directly including uncertainty in decisions. Procedures for quantifying and interpreting uncertainty in the practical application of such concepts are only beginning to evolve; much study is still required.[108 109 110 124 125]

b. In all applications of models an effort is encouraged to identify the reliability of the model estimates for that particular area and to determine the magnitude and sources of error associated with the use of the model. The analyst is responsible for recognizing and quantifying limitations in the accuracy, precision and sensitivity of the procedure. Information that might be useful to the decision-maker in recognizing the seriousness of potential air quality violations includes such model accuracy estimates as accuracy of peak predictions, bias, noise, correlation, frequency distribution, spatial extent of high concentration, etc. Both space/time pairing of estimates and measurements and unpaired comparisons are recommended. Emphasis should be on the highest concentrations and the averaging times of the standards or increments of concern. Where possible, confidence intervals about the statistical values should be provided. However, while such information can be provided by the modeler to the decision-maker, it is unclear how this information should be used to make an air pollution control decision. Given a range of possible outcomes, it is easiest and tends to ensure consistency if the decision-maker confines his judgement to use of the ''best estimate'' provided by the modeler (*i.e.,* the design concentration estimated by a model recommended in the *Guideline* or an alternate model of known accuracy). This is an indication of the practical limitations imposed by current abilities of the technical community.

c. To improve the basis for decision-making, EPA has developed and is continuing to study procedures for determining the accuracy of models, quantifying the uncertainty, and expressing confidence levels in decisions that are made concerning emissions controls.[126 127] However, work in this area involves ''breaking new ground'' with slow and sporadic progress likely. As a result, it may be necessary to continue using the ''best estimate'' until sufficient technical progress has been made to meaningfully implement such concepts dealing with uncertainty.

9.1.4 Evaluation of Models

a. A number of actions have been taken to ensure that the best model is used correctly for each regulatory application and that a model is not arbitrarily imposed. First, the *Guideline* clearly recommends the most appropriate model be used in each case. Preferred models, based on a number of factors, are identified for many uses. General guidance on using alternatives to the preferred models is also provided. Second, the models have been subjected to a systematic performance evaluation and a peer scientific review. Statistical performance measures, including measures of difference (or residuals) such as bias, variance of difference and gross variability of the difference, and measures of correlation such as time, space, and time and space combined as recommended by the AMS Woods Hole Workshop [11], were generally followed. Third, more specific information has been provided for justifying the site specific use of alternative models in previously cited EPA guidance [15], and new models are under consideration and review.[16] Together these documents provide methods that allow a judgement to be made as to what models are most appropriate for a specific application. For the present, performance and the theoretical evaluation of models are being used as an indirect means to quantify one element of uncertainty in air pollution regulatory decisions.

b. EPA has participated in a series of conferences entitled, ''Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes.'' [128] for the purpose of promoting the development of improved methods for the characterization of model performance. There is a consensus developing on what should be considered in the evaluation of air quality models [129], namely quality assurance planning, documentation and scrutiny should be consistent with the intended use, and should include:

- Scientific peer review;
- Supportive analyses (diagnostic evaluations, code verification, sensitivity and uncertainty analyses);
- Diagnostic and performance evaluations with data obtained in trial locations, and
- Statistical performance evaluations in the circumstances of the intended applications.

Performance evaluations and diagnostic evaluations assess different qualities of how well a model is performing, and both are needed to establish credibility within the client and scientific community. Performance evaluations allow us to decide how well the model simulates the average temporal and spatial patterns seen in the observations, and employ large spatial/temporal scale data sets (*e.g.,* national data sets). Performance evaluations also allow determination of relative performance of a model in comparison with alternative modeling systems. Diagnostic evaluations allow determination of a model capability to simulate individual processes that affect the results, and usually employ smaller spatial/temporal scale date sets (*e.g.,* field studies). Diagnostic evaluations allow us to decide if we get the right answer for the right reason. The objective comparison of modeled concentrations with observed field data provides only a partial means for assessing model performance. Due to the limited supply of evaluation data sets, there are severe practical limits in assessing model performance. For this reason, the conclusions reached in the science peer reviews and the supportive analyses have particular relevance in deciding whether a model will be useful for its intended purposes.

c. To extend information from diagnostic and performance evaluations, sensitivity and uncertainty analyses are encouraged since they can provide additional information on the effect of inaccuracies in the data bases and on the uncertainty in model estimates. Sensitivity analyses can aid in determining the effect of inaccuracies of variations or uncertainties in the data bases on the range of likely concentrations. Uncertainty analyses can aid in determining the range of likely concentration values, resulting from uncertainties in the model inputs, the model formulations, and parameterizations. Such information may be used to determine source impact and to evaluate control strategies. Where possible, information from such sensitivity analyses should be made available to the decision-maker with an appropriate interpretation of the effect on the critical concentrations.

9.2 Recommendations

a. No specific guidance on the quantification of model uncertainty for use in decision-making is being given at this time. As procedures for considering uncertainty develop and become implementable, this guidance will be changed and expanded. For the present, continued use of the ''best estimate'' is acceptable; however, in specific circumstances for O_3, PM–2.5 and regional haze, additional information and/or procedures may be appropriate.[32 33]

10.0 Regulatory Application of Models

10.1 Discussion

a. Procedures with respect to the review and analysis of air quality modeling and data analyses in support of SIP revisions, PSD permitting or other regulatory requirements need a certain amount of standardization to ensure consistency in the depth and comprehensiveness of both the review and the analysis itself. This section recommends procedures that permit some degree of standardization while at the same time allowing the flexibility needed to assure the technically best analysis for each regulatory application.

b. Dispersion model estimates, especially with the support of measured air quality data, are the preferred basis for air quality demonstrations. Nevertheless, there are instances where the performance of recommended dispersion modeling techniques, by comparison with observed air quality data, may be shown to be less than acceptable. Also, there may be no recommended modeling procedure suitable for the situation. In these instances, emission limitations may be established solely on the basis of observed air quality data as would be applied to a modeling analysis. The same care should be given to the analyses of the air quality data as would be applied to a modeling analysis.

c. The current NAAQS for SO_2 and CO are both stated in terms of a concentration not to be exceeded more than once a year. There is only an annual standard for NO_2 and a quarterly standard for Pb. Standards for fine particulate matter (PM–2.5) are expressed in terms of both long-term (annual) and short-term (daily) averages. The long-term standard is calculated using the three year average of the annual averages while the short-term standard is calculated using the three year average of the 98th percentile of the daily average concentration. For PM–10, the convention is to compare the arithmetic mean, averaged over 3 consecutive years, with the concentration specified in the NAAQS (50 μg/m³). The 24-hour NAAQS (150 μg/m³) is met if, over a 3-year period, there is (on average) no more than one exceedance per year. As noted in subsection 7.2.1.1, the modeled compliance for this NAAQS is based on the highest 6th highest concentration over 5 years. For ozone the short term 1-hour standard is expressed in terms of an expected exceedance limit while the short term 8-hour standard is expressed in terms of a three year average of the annual fourth highest daily maximum 8-hour value. The NAAQS are subjected to extensive review and possible revision every 5 years.

d. This section discusses general requirements for concentration estimates and identifies the relationship to emission limits. The following recommendations apply to: (1) Revisions of State Implementation Plans and (2) the review of new sources and the prevention of significant deterioration (PSD).

10.2 Recommendations

10.2.1 Analysis Requirements

a. Every effort should be made by the Regional Office to meet with all parties involved in either a SIP revision or a PSD permit application prior to the start of any work on such a project. During this meeting, a protocol should be established between the preparing and reviewing parties to define the procedures to be followed, the data to be collected, the model to be used, and the analysis of the source and concentration data. An example of requirements for such an effort is contained in the Air Quality Analysis Checklist posted on EPA's Internet SCRAM Web site (subsection 2.3). This checklist suggests the level of detail required to assess the air quality resulting from the proposed action. Special cases may require additional data collection or analysis and this should be determined and agreed upon at this preapplication meeting. The protocol should be written and agreed upon by the parties concerned, although a formal legal document is not intended. Changes in such a protocol are often required as the data collection and analysis progresses. However, the protocol establishes a common understanding of the requirements.

b. An air quality analysis should begin with a screening model to determine the potential of the proposed source or control strategy to violate the PSD increment or NAAQS. For traditional stationary sources, EPA guidance [24] should be followed. Guidance is also available for mobile sources.[48]

c. If the concentration estimates from screening techniques indicate a significant impact or that the PSD increment or NAAQS may be approached or exceeded, then a more refined modeling analysis is appropriate and the model user should select a model according to recommendations in Sections 4–8. In some instances, no refined technique may be specified in this guide for the situation. The model user is then encouraged to submit a model developed specifically for the case at hand. If that is not possible, a screening technique may supply the needed results.

d. Regional Offices should require permit applicants to incorporate the pollutant contributions of all sources into their analysis. Where necessary this may include emissions associated with growth in the area of impact of the new or modified source. PSD air quality assessments should consider the amount of the allowable air quality increment that has already been consumed by other sources. Therefore, the most recent source applicant should model the existing or permitted sources in addition to the one currently under consideration. This would permit the use of newly acquired data or improved modeling techniques if such have become available since the last source was permitted. When remodeling, the worst case used in the previous modeling analysis should be one set of conditions modeled in the new analysis. All sources should be modeled for each set of meteorological conditions selected.

10.2.2 Use of Measured Data in Lieu of Model Estimates

a. Modeling is the preferred method for determining emission limitations for both new and existing sources. When a preferred model is available, model results alone (including background) are sufficient. Monitoring will normally not be accepted as the sole basis for emission limitation. In some instances when the modeling technique available is only a screening technique, the addition of air quality data to the analysis may lend credence to model results.

b. There are circumstances where there is no applicable model, and measured data may need to be used. However, only in the case of a NAAQS assessment for an existing source should monitoring data alone be a basis for emission limits. In addition, the following items (i–vi) should be considered prior to the acceptance of the measured data:

i. Does a monitoring network exist for the pollutants and averaging times of concern?

ii. Has the monitoring network been designed to locate points of maximum concentration?

iii. Do the monitoring network and the data reduction and storage procedures meet EPA monitoring and quality assurance requirements?

iv. Do the data set and the analysis allow impact of the most important individual sources to be identified if more than one source or emission point is involved?

v. Is at least one full year of valid ambient data available?

vi. Can it be demonstrated through the comparison of monitored data with model results that available models are not applicable?

c. The number of monitors required is a function of the problem being considered. The source configuration, terrain configuration, and meteorological variations all have an impact on number and placement of monitors. Decisions can only be made on a case-by-case basis. Guidance is available for establishing criteria for demonstrating that a model is not applicable?

d. Sources should obtain approval from the appropriate reviewing authority (paragraph 3.0(b)) for the monitoring network prior to the start of monitoring. A monitoring protocol agreed to by all concerned parties is highly desirable. The design of the network, the number, type and location of the monitors, the sampling period, averaging time as well as the need for meteorological monitoring or the use of mobile sampling or plume tracking techniques, should all be specified in the protocol and agreed upon prior to start-up of the network.

10.2.3 Emission Limits

10.2.3.1 Design Concentrations

a. Emission limits should be based on concentration estimates for the averaging time that results in the most stringent control requirements. The concentration used in specifying emission limits is called the design value or design concentration and is a sum of the concentration contributed by the primary source, other applicable sources, and—for NAAQS assessments—the background concentration.

b. To determine the averaging time for the design value, the most restrictive NAAQS or PSD increment, as applicable, should be identified. For a NAAQS assessment, the averaging time for the design value is determined by calculating, for each averaging time, the ratio of the difference between the applicable NAAQS (S) and the background concentration (B) to the (model) predicted concentration (P) (*i.e.*, (S–B)/P). For a PSD increment assessment, the averaging time for the design value is determined by calculating, for each averaging time, the ratio of the applicable PSD increment (I) and the model-predicted concentration (P) (*i.e.*, I/P). The averaging time with the lowest ratio identifies the most restrictive standard or increment. If the annual average is the most restrictive, the highest estimated annual average concentration from one or a number of years of data is the design value. When short term standards are most restrictive, it may be necessary to consider a broader range of concentrations than the highest value. For example, for pollutants such as SO_2, the highest, second-highest concentration is the design value. For pollutants with statistically based NAAQS, the design value is found by determining the more restrictive of: (1) The short-term concentration over the period specified in the standard, or (2) the long-term concentration that is not expected to exceed the long-term NAAQS. Determination of design values for PM–10 is presented in more detail in EPA guidance.[34]

10.2.3.2 NAAQS Analyses for New or Modified Sources

a. For new or modified sources predicted to have a significant ambient impact [83] and to be located in areas designated attainment or unclassifiable for the SO_2, Pb, NO_2, or CO NAAQS, the demonstration as to whether the source will cause or contribute to an air quality violation should be based on: (1) The highest estimated annual average concentration determined from annual averages of individual years; or (2) the highest, second-highest estimated concentration for averaging times of 24-hours or less; and (3) the significance of the spatial and temporal contribution to any modeled violation. For Pb, the highest estimated concentration based on an individual calendar quarter averaging period should be used. Background concentrations should be added to the estimated impact of the source. The most restrictive standard should be used in all cases to assess the threat of an air quality violation. For new or modified sources predicted to have a significant ambient impact[83] in areas designated attainment or unclassifiable for the PM–10 NAAQS, the demonstration of whether or not the source will cause or contribute to an air quality violation should be based on sufficient data to show whether: (1) The projected 24-hour average concentrations will exceed the 24-hour NAAQS more than once per year, on average; (2) the expected (i.e., average) annual mean concentration will exceed the annual NAAQS; and (3) the source contributes significantly, in a temporal and spatial sense, to any modeled violation.

10.2.3.3 PSD Air Quality Increments and Impacts

a. The allowable PSD increments for criteria pollutants are established by regulation and cited in 40 CFR 51.166. These maximum allowable increases in pollutant concentrations may be exceeded once per year at each site, except for the annual increment that may not be exceeded. The highest, second-highest increase in estimated concentrations for the short term averages as determined by a model should be less than or equal to the permitted increment. The modeled annual averages should not exceed the increment.

b. Screening techniques defined in subsection 4.2.1 can sometimes be used to estimate short term incremental concentrations for the first new source that triggers the baseline in a given area. However, when multiple increment-consuming sources are involved in the calculation, the use of a refined model with at least 1 year of site specific or 5 years of (off-site) NWS data is normally required (subsection 8.3.1.2). In such cases, sequential modeling must demonstrate that the allowable increments are not exceeded temporally and spatially, *i.e.*, for all receptors for each time period throughout the year(s) (time period means the appropriate PSD averaging time, *e.g.*, 3-hour, 24-hour, *etc.*).

c. The PSD regulations require an estimation of the SO_2, particulate matter (PM–10), and NO_2 impact on any Class I area. Normally, steady-state Gaussian plume models should not be applied at distances greater than can be accommodated by the steady state assumptions inherent in such models. The maximum distance for refined steady-state Gaussian plume model application for regulatory purposes is generally considered to be 50km. Beyond the 50km range, screening techniques may be used to determine if more refined modeling is needed. If refined models are needed, long range transport models should be considered in accordance with subsection 6.2.3. As previously noted in Sections 3 and 7, the need to involve the Federal Land Manager in decisions on potential air quality impacts, particularly in relation to PSD Class I areas, cannot be overemphasized.

11.0 Bibliography[a]

American Meteorological Society. Symposia on Turbulence, Diffusion, and Air Pollution (1st–10th); 1971–1992. Symposia on Boundary Layers & Turb. 11th–12th; 1995–1997. Boston, MA.

American Meteorological Society, 1977–1998. Joint Conferences on Applications of Air Pollution Meteorology (1st–10th). Sponsored by the American Meteorological Society and the Air & Waste Management Association. Boston, MA.

American Meteorological Society, 1978. Accuracy of Dispersion Models. *Bulletin of the American Meteorological Society*, 59(8): 1025–1026.

American Meteorological Society, 1981. Air Quality Modeling and the Clean Air Act: Recommendations to EPA on Dispersion Modeling for Regulatory Applications. Boston, MA.

Briggs, G.A., 1969. Plume Rise. U.S. Atomic Energy Commission Critical Review Series, Oak Ridge National Laboratory, Oak Ridge, TN.

Drake, R.L. and S.M. Barrager, 1979. Mathematical Models for Atmospheric Pollutants. EPRI EA–1131. Electric Power Research Institute, Palo Alto, CA.

Environmental Protection Agency, 1978. Workbook for Comparison of Air Quality Models. Publication No. EPA–450/2–78–028a and b. Office of Air Quality Planning & Standards, Research Triangle Park, NC.

Erisman J.W., Van Pul A. and Wyers P. (1994) Parameterization of surface resistance for the quantification of atmospheric deposition of acidifying pollutants and ozone. *Atmos. Environ.*, 28: 2595–2607.

Fox, D.G., and J.E. Fairobent, 1981. NCAQ Panel Examines Uses and Limitations of Air Quality Models. *Bulletin of the American Meteorological Society*, 62(2): 218–221.

Gifford, F.A., 1976. Turbulent Diffusion Typing Schemes: A Review. *Nuclear Safety*, 17(1): 68–86.

Gudiksen, P.H., and M.H. Dickerson, Eds., Executive Summary: Atmospheric Studies in Complex Terrain Technical Progress Report FY–1979 Through FY–1983. Lawrence Livermore National Laboratory, Livermore, CA. (Docket Reference No. II–I–103).

Hanna, S.R., G.A. Briggs, J. Deardorff, B.A. Egan, G.A. Gifford and F. Pasquill, 1977. AMS Workshop on Stability Classification Schemes And Sigma Curves—Summary of Recommendations. *Bulletin of the American Meteorological Society*, 58(12): 1305–1309.

Hanna, S.R., G.A. Briggs and R.P. Hosker, Jr., 1982. Handbook on Atmospheric Diffusion. Technical Information Center, U.S. Department of Energy, Washington, D.C.

Haugen, D.A., Workshop Coordinator, 1975. Lectures on Air Pollution and Environmental Impact Analyses. Sponsored by the American Meteorological Society, Boston, MA.

Hoffnagle, G.F., M.E. Smith, T.V. Crawford and T.J. Lockhart, 1981. On-site Meteorological Instrumentation Requirements to Characterize Diffusion from Point Sources—A Workshop, 15–17 January 1980, Raleigh, NC. *Bulletin of the American Meteorological Society*, 62(2): 255–261.

Hunt, J.C.R., R.G. Holroyd, D.J. Carruthers, A.G. Robins, D.D. Apsley, F.B. Smith and D.J. Thompson, 1990. Developments in Modeling Air Pollution for Regulatory Uses. *In* Proceedings of the 18th NATO/CCMS International Technical Meeting on Air Pollution Modeling and its Application, Vancouver, Canada. Also *In* Air Pollution Modeling and its Application VIII (1991). H. van Dop and D.G. Steyn, eds. Plenum Press, New York, NY. pp. 17–59

Pasquill, F. and F.B. Smith, 1983. Atmospheric Diffusion, 3rd Edition. Ellis Horwood Limited, Chichester, West Sussex, England, 438pp.

Randerson, D., Ed., 1984. Atmospheric Science and Power Production. DOE/TIC 2760l. Office of Scientific and Technical Information, U.S. Department of Energy, Oak Ridge, TN.

Scire, J.S. and L.L. Schulman, 1980: Modeling plume rise from low-level buoyant line and point sources. AMS/APCA Second Joint Conference on Applications of Air Pollution Meteorology, March 24–27, New Orleans, LA.

Smith, M.E., Ed., 1973. Recommended Guide for the Prediction of the Dispersion of Airborne Effluents. The American Society of Mechanical Engineers, New York, NY.

Stern, A.C., Ed., 1976. *Air Pollution, Third Edition, Volume I: Air Pollutants, Their Transformation and Transport.* Academic Press, New York, NY.

Turner, D.B., 1979. Atmospheric Dispersion Modeling: A Critical Review. *Journal of the Air Pollution Control Association*, 29(5): 502–519.

Venkatram, A. and J.C. Wyngaard, Editors, 1988. *Lectures on Air Pollution Modeling.* American Meteorological Society, Boston, MA. 390pp.

12.0 References

1. Code of Federal Regulations; Title 40 (Protection of Environment). Sections 51.112, 51.117, 51.150, 51.160.

2. Environmental Protection Agency, 1990. New Source Review Workshop Manual: Prevention of Significant Deterioration and Nonattainment Area Permitting (Draft). Office of Air Quality Planning & Standards, Research Triangle Park, NC. (Available at: *http://www.epa.gov/ttn/nsr/*)

3. Code of Federal Regulations; Title 40 (Protection of Environment). Sections 51.166 and 52.21.

4. Code of Federal Regulations (Title 40, Part 50): Protection of the Environment; National Primary and Secondary Ambient Air Quality Standards.

5. Environmental Protection Agency, 1988. Model Clearinghouse: Operational Plan (Revised). Staff Report. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (Docket No. A–88–04, II–J–1)

6. Environmental Protection Agency, 1980. Guidelines on Air Quality Models. **Federal Register**, 45(61): 20157–20158.

7. Scire, J.S. and L.L. Schulman, 1981. Evaluation of the BLP and ISC Models with SF6 Tracer Data and SO_2 Measurements at Aluminum Reduction Plants. APCA Specialty Conference on Dispersion

[a] The documents listed here are major sources of supplemental information on the theory and application of mathematical air quality models.

Modeling for Complex Sources, St. Louis, MO.

8. Environmental Protection Agency, 1986. Evaluation of Mobile Source Air Quality Simulation Models. Publication No. EPA–450/4–86–002. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (NTIS No. PB 86–167293)

9. Strimaitis, D.G., J.S. Scire and J.C. Chang. 1998. Evaluation of the CALPUFF Dispersion Model with Two Power Plant Data Sets. Tenth Joint Conference on the Application of Air Pollution Meteorology, Phoenix, Arizona. American Meteorological Society, Boston, MA. January 11–16, 1998.

10. Environmental Protection Agency, 2003. AERMOD: Latest Features and Evaluation Results. Publication No. EPA–454/R–03–003. U.S. Environmental Protection Agency, Research Triangle Park, NC. (Available at *http://www.epa.gov/scram001/*)

11. Fox, D.G., 1981. Judging Air Quality Model Performance. *Bulletin of the American Meteorological Society*, 62(5): 599–609.

12. American Meteorological Society, 1983. Synthesis of the Rural Model Reviews. Publication No. EPA–600/3–83–108. Office of Research & Development, Research Triangle Park, NC. (NTIS No. PB 84–121037)

13. Allwine, K.J., W.F. Dabberdt and L.L. Simmons. 1998. Peer Review of the CALMET/CALPUFF Modeling System. Prepared by the KEVRIC Company, Inc. under EPA Contract No. 68–D–98–092 for Environmental Protection Agency, Research Triangle Park, NC. (Docket No. A–99–05, II–A–8)

14. Hanna, S., M. Garrison and B. Turner, 1998. AERMOD Peer Review report. Prepared by SAI, Inc. under EPA Contract No. 68–D6–0064/1–14 for Environmental Protection Agency, Research Triangle Park, NC. 12pp. & appendices (Docket No. A–99–05, II–A–6)

15. Environmental Protection Agency, 1992. Protocol for Determining the Best Performing Model. Publication No. EPA–454/R–92–025. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (NTIS No. PB 93–226082)

16. ASTM D6589: Standard Guide for Statistical Evaluation of Atmospheric Dispersion Model Performance. (2000)

17. Environmental Protection Agency, 1995. User's Guide for the Industrial Source Complex (ISC3) Dispersion Models, Volumes 1 and 2. Publication Nos. EPA–454/B–95–003a & b. U.S. Environmental Protection Agency, Research Triangle Park, NC. (NTIS Nos. PB 95–222741 and PB 95–222758, respectively)

18. Hanna, S.R. and R.J. Paine, 1989. Hybrid Plume Dispersion Model (HPDM) Development and Evaluation. *J. Appl. Meteorol.*, 28: 206–224.

19. Hanna, S.R. and J.C. Chang, 1992. Boundary layer parameterizations for applied dispersion modeling over urban areas. Bound. Lay. Meteorol., 58, 229–259.

20. Hanna, S.R. and J.C. Chang, 1993. Hybrid Plume Dispersion Model (HPDM) Improvements and Testing at Three Field Sites. Atmos. Environ., 27A: 1491–1508.

21. American Meteorological Society, 1984. Workshop on Updating Applied Diffusion Models. 24–27 January 1984. Clearwater, Florida. J. Climate and Appl. Met., 24(11): 1111—1207.

22. Environmental Protection Agency, 2002. AERMOD: Description of Model Formulation. Research Triangle Park, NC. EPA Report No. EPA–454/R–02–002d; April 2002; AND Cimorelli, A. *et al.*, 2005. AERMOD: A Dispersion Model for Industrial Source Applications. Part I: General Model Formulation and Boundary Layer Characterization. *Journal of Applied Meteorology*, 44(5): 682–693.

23. L.L. Schulman, D.G. Strimaitis and J.S. Scire, 2002. Development and evaluation of the PRIME plume rise and building downwash model. *Journal of the Air & Waste Management Association*, 50: 378–390.

24. Environmental Protection Agency, 1992. Screening Procedures for Estimating the Air Quality Impact of Stationary Sources, Revised. Publication No. EPA–454/R–92–019. U.S. Environmental Protection Agency, Research Triangle Park, NC. (NTIS No. PB 93–219095)

25. Environmental Protection Agency, 1995. SCREEN3 User's Guide. Publication No. EPA–454/B–95–004. U.S. Environmental Protection Agency, Research Triangle Park, NC. (NTIS No. PB 95–222766)

26. Perry, S.G., D.J. Burns and A.J. Cimorelli, 1990. User's Guide to CTDMPLUS: Volume 2. The Screening Mode (CTSCREEN). Publication No. EPA–600/8–90–087. U.S. Environmental Protection Agency, Research Triangle Park, NC. (NTIS No. PB 91–136564)

27. Mills, M.T., R.J. Paine, E.A. Insley and B.A. Egan, 1987. The Complex Terrain Dispersion Model Terrain Preprocessor System—User's Guide and Program Description. Publication No. EPA–600/8–88–003. U.S. Environmental Protection Agency, Research Triangle Park, NC. (NTIS No. PB 88–162094)

28. Burns, D.J., S.G. Perry and A.J. Cimorelli, 1991. An Advanced Screening Model for Complex Terrain Applications. Paper presented at the 7th Joint Conference on Applications of Air Pollution Meteorology (cosponsored by the American Meteorological Society and the Air & Waste Management Association), January 13–18, 1991, New Orleans, LA.

29. Environmental Research and Technology, 1987. User's Guide to the Rough Terrain Diffusion Model (RTDM), Rev. 3.20. ERT Document No. P–D535–585. Environmental Research and Technology, Inc., Concord, MA. (NTIS No. PB 88–171467)

30. Meng, Z.D. Dabdub and J.H. Seinfeld, 1997. Chemical Coupling between Atmospheric Ozone and Particulate Matter. *Science*, 277: 116–119.

31. Hidy, G.M, P.M. Roth, J.M. Hales and R.D. Scheffe, 1998. Fine Particles and Oxidant Pollution: Developing an Agenda for Cooperative Research. *JAWMA*, 50: 613–632.

32. Environmental Protection Agency, 2005. Guidance on the Use of Models and Other Analyses in Attainment Demonstrations for the 8-hr Ozone NAAQS (Draft Final). Office of Air Quality Planning & Standards, Research Triangle Park, NC. (Latest version available on SCRAM Web site as *draft-final-O3.pdf*; *see* subsection 2.3)

33. Environmental Protection Agency, 2005. Guidance on the Use of Models and Other Analyses in Attainment Demonstrations for the PM–2.5 NAAQS and Regional Haze Goals. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (As of May 2005, this document has not been finalized; latest version available on SCRAM Web site as *draft-pm.pdf; see* subsection 2.3)

34. Environmental Protection Agency, 1987. PM–10 SIP Development Guideline. Publication No. EPA–450/2–86–001. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (NTIS No. PB 87–206488)

35. U.S. Forest Service, 1996. User Assessment of Smoke-Dispersion Models for Wildland Biomass Burning. USDA, Pacific Northwest Research Station, Portland, OR. General Technical Report PNW–GTR–379. 30pp. (NTIS No. PB 97–163380)

36. Hanrahan, P.L., 1999. The Polar Volume Polar Ratio Method for Determining NO_2 / NO_X Ratios in Modeling—Part I: Methodology. *J. Air & Waste Manage. Assoc.*, 49: 1324–1331.

37. Environmental Protection Agency, 1997. Guidance for Siting Ambient Air Monitors around Stationary Lead Sources. Publication No. EPA–454/R–92–009R. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (NTIS No. PB 97–208094)

38. Environmental Protection Agency, 1993. Lead Guideline Document. Publication No. EPA–452/R–93–009. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (NTIS No. PB 94–111846)

39. Environmental Protection Agency, 1998. EPA Third-Generation Air Quality Modeling System. Models-3, Volume 9b: User Manual. Publication No. EPA–600/R–98/069(b). Office of Research and Development, Washington, D.C.

40. Gery, M.W. and R.R. Crouse, 1991. User's Guide for Executing OZIPR. Publication No. EPA–600/8–90–069. Office of Research & Development, Research Triangle Park, NC. (NTIS No. PB 91–175877)

41. Environmental Protection Agency, 2002. User's Guide to the Regulatory Modeling System for Aerosols and Deposition (REMSAD) Version 7. Prepared for Environmental Protection Agency under Contract No. GS–10F–0124J by ICF Consulting, July 2002. (Available at *http://www.epa.gov/scram001/*)

42. Environmental Protection Agency, 2004. EPA–CMB8.2 Users Manual. Publication No. EPA–452/R–04–011. Office of Air Quality Planning & Standards, Research Triangle Park, NC; December 2004. (Available at *http://www.ega.gov/scram001/*)

43. Environmental Protection Agency, 2004. Protocol for Applying and Validating the CMB Model for $PM_{2.5}$ and VOC. Publication No. EPA–451/R–04–001. Office of Air Quality Planning & Standards, Research Triangle Park, NC; December 2004. (Available at *http://www.ega.gov/scram001/*)

44. Environmental Protection Agency, 1988. Chemical Mass Balance Model Diagnostics. Publication No. EPA–450/4–88–005. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (NTIS No. PB 88–208319)

45. Paatero, P. and U. Tapper, 1994. Positive Matrix Factorization: A Non-

negative Factor Model with Optimal Utilization of Error Estimates of Data Values. *Environmetrics*, 5: 111–126. (Other documents related to PMF may be accessed via FTP at *ftp://rock.helsinki.fi/pub/misc/pmf.*)

46. Lewis, C.W., G.A. Norris, R.C. Henry and T.L. Conner, 2003. Source Apportionment of Phoenix PM–2.5 Aerosol with the Unmix Receptor Model. *Journal of the Air & Waste Management Association*, 53(3): 325–338.

47. Environmental Protection Agency, 1994. Guidelines for PM10 Sampling and Analysis Applicable to Receptor Modeling. Publication No. EPA–452/R–94–009. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (NTIS No. PB 94–177441)

48. Environmental Protection Agency, 1992. Guideline for Modeling Carbon Monoxide from Roadway Intersections. Publication No. EPA–454/R–92–005. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (NTIS No. PB 93–210391)

49. Environmental Protection Agency, 1992. User's Guide for CAL3QHC Version 2: A Modeling Methodology for Predicting Pollutant Concentrations near Roadway Intersections. Publication No. EPA–454/R–92–006. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (NTIS No. PB 93–210250)

50. Environmental Protection Agency, 1992. Evaluation of CO Intersection Modeling techniques Using a New York City Database. Publication No. EPA–454/R–92–004. Office of Air Quality Planning & Standards, RTP, NC 27711. (NTIS No. PB 93–105559)

51. Environmental Protection Agency, 1995. Addendum to the User's Guide to CAL3QHC Version 2.0. Staff Report. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (Available at *http://www.epa.gov/scram001/*)

52. Shannon, J.D., 1987. Mobile Source Modeling Review. A report prepared under a cooperative agreement with the Environmental Protection Agency. 5pp. (Docket No. A–88–04, II–J–2)

53. Environmental Protection Agency, 1991. Emission Inventory Requirements for Carbon Monoxide State Implementation Plans. Publication No. EPA–450/4–91–011. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (NTIS No. PB 92–112150)

54. Environmental Protection Agency, 1992. Guideline for Regulatory Application of the Urban Airshed Model for Areawide Carbon Monoxide. Publication No. EPA–450/4–92–011a and b. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (NTIS Nos. PB 92–213222 and PB 92–213230)

55. Environmental Protection Agency, 1992. Technical Support Document to Aid States with the Development of Carbon Monoxide State Implementation Plans. Publication No. EPA–452/R–92–003. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (NTIS No. PB 92–233055)

56. Chu, S.H. and E.L. Meyer, 1991. Use of Ambient Ratios to Estimate Impact of NO_X Sources on Annual NO_2 Concentrations. Proceedings, 84th Annual Meeting & Exhibition of the Air & Waste Management Association, Vancouver, B.C.; 16–21 June 1991. (16pp.) (Docket No. A–92–65, II–A–9)

57. Cole, H.S. and J.E. Summerhays, 1979. A Review of Techniques Available for Estimation of Short-Term NO_2 Concentrations. *Journal of the Air Pollution Control Association*, 29(8): 812–817.

58. U.S. Department of Housing and Urban Development, 1980. Air Quality Considerations in Residential Planning. U.S. Superintendent of Documents, Washington, DC. (GPO Order Nos. 023–000–00577–8, 023–000–00576–0, 023–000–00575–1)

59. Environmental Protection Agency, 1986. Evaluation of Short-Term Long-Range Transport Models, Volumes I and II. Publication Nos. EPA–450/4–86–016a and b. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (NTIS Nos. PB 87–142337 and PB 87–142345)

60. Environmental Protection Agency, 1998. Interagency Workgroup on Air Quality Modeling (IWAQM) Phase 2 Summary Report and Recommendations for Modeling Long-Range Transport Impacts. Publication No. EPA–454/R–98–019. Office of Air Quality Planning & Standards, Research Triangle Park, NC.(NTIS No. PB 99–121089)

61. National Acid Precipitation Assessment Program (NAPAP), 1991. Acid Deposition: State of Science and Technology. Volume III Terrestrial, Materials, Health and Visibility Effects. Report 24, *Visibility: Existing and Historical Conditions—Causes and Effects* Edited by Patricia M. Irving. Washington, DC 129pp.

62. National Research Council, 1993. Protecting Visibility in National Parks and Wilderness Areas. National Academy Press, Washington, DC 446pp.

63. Environmental Protection Agency, 1992. Workbook for Plume Visual Impact Screening and Analysis (Revised). Publication No. EPA–454/R–92–023. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (NTIS No. PB 93–223592)

64. Environmental Protection Agency, 1981. Guideline for Use of Fluid Modeling to Determine Good Engineering Practice (GEP) Stack Height. Publication No. EPA–450/4–81–003. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (NTIS No. PB 82–145327)

65. Lawson, Jr., R.E. and W.H. Snyder, 1983. Determination of Good Engineering Practice Stack Height: A Demonstration Study for a Power Plant. Publication No. EPA–600/3–83–024. Office of Research & Development, Research Triangle Park, NC. (NTIS No. PB 83–207407)

66. Environmental Protection Agency, 1985. Guideline for Determination of Good Engineering Practice Stack Height (Technical Support Document for the Stack Height Regulations), Revised. Publication No. EPA–450/4–80–023R. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (NTIS No. PB 85–225241)

67. Snyder, W.H. and R.E. Lawson, Jr., 1985. Fluid Modeling Demonstration of Good Engineering-Practice Stack Height in Complex Terrain. Publication No. EPA–600/3–85–022. Office of Research & Development, Research Triangle Park, NC. (NTIS No. PB 85–203107)

68. Bennett, M.J, M.E. Yansura, I.G. Hornyik, J.M. Nall, D.G. Caniparoli and C.G. Ashmore, 2002. Evaluation of the CALPUFF Long-range Transport Screening Technique by Comparison to Refined CALPUFF Results for Several Power Plants in Both the Eastern and Western United States. Proceedings of the Air & Waste Management Association's 95th Annual Conference, June 23–27, 2002; Baltimore, MD. Paper #43454.

69. Environmental Protection Agency, 1999. Guideline of Data Handling Conventions for the PM NAAQS. Publication No. EPA–454/R–99–008. Office of Air Quality Planning & Standards, Research Triangle Park. (NTIS PB 99–149023)

70. Turner, D.B., 1969. Workbook of Atmospheric Dispersion Estimates. PHS Publication No. 999–AP–26. U.S. Department of Health, Education and Welfare, Public Health Service, Cincinnati, OH. (NTIS No. PB–191482)

71. McElroy, J.L. and F. Pooler, Jr., 1968. St. Louis Dispersion Study, Volume II—Analysis. National Air Pollution Control Administration Publication No. AP–53, U.S. Department of Health, Education and Welfare, Public Health Service, Arlington, VA. (NTIS No. PB–190255)

72. Irwin, J.S., 1978. Proposed Criteria for Selection of Urban Versus Rural Dispersion Coefficients. (Draft Staff Report). Meteorology and Assessment Division, U.S. Environmental Protection Agency, Research Triangle Park, NC. (Docket No. A–80–46, II-B–8)

73. Auer, Jr., A.H., 1978. Correlation of Land Use and Cover with Meteorological Anomalies. *Journal of Applied Meteorology*, 17(5): 636–643.

74. Pasquill, F., 1976. Atmospheric Dispersion Parameters in Gaussian Plume Modeling, Part II. Possible Requirements for Change in the Turner Workbook Values. Publication No. EPA–600/4–76–030b. Office of Research & Development, Research Triangle Park, NC. (NTIS No. PB–258036/3BA)

75. Turner, D.B., 1964. A Diffusion Model for an Urban Area. *Journal of Applied Meteorology*, 3(1): 83–91.

76. Briggs, G.A., 1975. Plume Rise Predictions. Chapter 3 in Lectures on Air Pollution and Environmental Impact Analyses. American Meteorological Society, Boston, MA; pp. 59–111.

77. Hanna, S.R., G.A. Briggs and R.P. Hosker, Jr., 1982. Plume Rise. Chapter 2 in *Handbook on Atmospheric Diffusion*. Technical Information Center, U.S. Department of Energy, Washington, DC; pp. 11–24. DOE/TIC–11223 (DE 82002045)

78. Weil, J.C., L.A. Corio and R.P. Brower, 1997. A PDF dispersion model for buoyant plumes in the convective boundary layer. *Journal of Applied Meteorology*, 36: 982–1003.

79. Stull, R.B., 1988. An Introduction to Boundary Layer Meteorology. Kluwer Academic Publishers, Boston, MA. 666pp.

80. Environmental Protection Agency, 1988. User's Guide to SDM—A Shoreline Dispersion Model. Publication No. EPA–450/

4–88–017. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (NTIS No. PB 89–164305)

81. Environmental Protection Agency, 1987. Analysis and Evaluation of Statistical Coastal Fumigation Models. Publication No. EPA–450/4–87–002. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (NTIS No. PB 87–175519)

82. Environmental Protection Agency, 1995. Compilation of Air Pollutant Emission Factors, Volume I: Stationary Point and Area Sources (Fifth Edition, AP–42: GPO Stock No. 055–000–00500–1), and Supplements A–D; Volume II: Mobile Sources (Fifth Edition). Office of Air Quality Planning & Standards, Research Triangle Park, NC. Volume I can be downloaded from EPA's Internet Web site at *http://www.epa.gov/ttn/chief/ap42.html*; Volume II can be downloaded from *http://www.epa.gov/omswww/ap42.htm*

83. Environmental Protection Agency, 1987. Ambient Air Monitoring Guidelines for Prevention of Significant Deterioration (PSD). Publication No. EPA–450/4–87–007. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (NTIS No. PB 90–168030)

84. Stauffer, D.R. and Seaman, N.L., 1990. Use of four-dimensional data assimilation in a limited-area mesoscale model. Part I: Experiments with synoptic-scale data. *Monthly Weather Review*, 118: 1250–1277.

85. Stauffer, D.R., N.L. Seaman and F.S. Binkowski, 1991. Use of four-dimensional data assimilation in a limited-area mesoscale model. Part II: Effect of data assimilation within the planetary boundary layer. *Monthly Weather Review*, 119: 734–754.

86. Grell, G.A., J. Dudhia, and D.R. Stauffer, 1994. A Description of the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5). *NCAR Technical Note*, NCAR/TN–398+STR, National Center for Atmospheric Research, Boulder, CO; 138pp. *http://www.mmm.ucar.edu/mm5/mm5-home.html*

87. Landsberg, H.E. and W.C. Jacobs, 1951. Compendium of Meteorology. American Meteorological Society, Boston, MA; pp. 976–992.

88. Burton, C.S., T.E. Stoeckenius and J.P. Nordin, 1983. The Temporal Representativeness of Short-Term Meteorological Data Sets: Implications for Air Quality Impact Assessments. Systems Applications, Inc., San Rafael, CA. (Docket No. A–80–46, II-G–11)

89. Solar and Meteorological Surface Observation Network, 1961–1990; 3-volume CD–ROM. Version 1.0, September 1993. Produced jointly by National Climatic Data Center and National Renewable Energy Laboratory. Can be ordered from NOAA National Data Center's Internet Web site at *http://www.NNDC.NOAA.GOV/*.

90. Hourly United States Weather Observations, 1990–1995 (CD–ROM). October 1997. Produced jointly by National Climatic Data Center and Environmental Protection Agency. Can be ordered from NOAA National Data Center's Internet Web site at *http://lwf.ncdc.noaa.gov/oa/ncdc.html*

91. Radiosonde Data of North America, 1946–1996; 4-volume CD–ROM. August 1996. Produced jointly by Forecast Systems laboratory and National Climatic Data Center. Can be ordered from NOAA National Data Center's Internet Web site at *http://lwf.ncdc.noaa.gov/oa/ncdc.html*

92. Environmental Protection Agency, 2000. Meteorological Monitoring Guidance for Regulatory Modeling Applications. Publication No. EPA–454/R–99–005. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (PB 2001–103606) (Available at *http://www.epa.gov/scram001/*)

93. ASTM D5527: Standard Practice for Measuring Surface Winds and Temperature by Acoustic Means. (1994)

94. ASTM D5741: Standard Practice for Characterizing Surface Wind Using Wind Vane and Rotating Anemometer. (1996)

95. Environmental Protection Agency, 1995. Quality Assurance for Air Pollution Measurement Systems, Volume IV—Meteorological Measurements. Publication No. EPA600/R–94/038d. Office of Air Quality Planning & Standards, Research Triangle Park, NC. *Note:* for copies of this handbook, you may make inquiry to ORD Publications, 26 West Martin Luther King Dr., Cincinatti, OH 45268. Phone (513) 569–7562 or (800) 490–9198 (automated request line)

96. Bowen, B.M., J.M. Dewart and A.I. Chen, 1983. Stability Class Determination: A Comparison for One Site. Proceedings, Sixth Symposium on Turbulence and Diffusion. American Meteorological Society, Boston, MA; pp. 211–214. (Docket No. A–92–65, II–A–7)

97. Environmental Protection Agency, 1993. An Evaluation of a Solar Radiation/Delta-T (SRDT) Method for Estimating Pasquill-Gifford (P–G) Stability Categories. Publication No. EPA–454/R–93–055. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (NTIS No. PB 94–113958)

98. Irwin, J.S., 1980. Dispersion Estimate Suggestion #8: Estimation of Pasquill Stability Categories. Office of Air Quality Planning & Standards, Research Triangle Park, NC (Docket No. A–80–46, II–B–10)

99. Mitchell, Jr., A.E. and K.O. Timbre, 1979. Atmospheric Stability Class from Horizontal Wind Fluctuation. Presented at 72nd Annual Meeting of Air Pollution Control Association, Cincinnati, OH; June 24–29, 1979. (Docket No. A–80–46, II–P–9)

100. Smedman—Hogstrom, A. and V. Hogstrom, 1978. A Practical Method for Determining Wind Frequency Distributions for the Lowest 200m from Routine Meteorological Data. *J. of Applied Meteorology*, 17(7): 942–954.

101. Smith, T.B. and S.M. Howard, 1972. Methodology for Treating Diffusivity. MRI 72 FR–1030. Meteorology Research, Inc., Altadena, CA. (Docket No. A–80–46, II–P–8)

102. Environmental Protection Agency, 2004. User's Guide for the AERMOD Meteorological Preprocessor (AERMET). Publication No. EPA–454/B–03–002. U.S. Environmental Protection Agency, Research Triangle Park, NC. (Available at *http://www.epa.gov/scram001/*)

103. Environmental Protection Agency, 1993. PCRAMMET User's Guide. Publication No. EPA–454/R–96–001. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (NTIS No. PB 97–147912)

104. Environmental Protection Agency, 1996. Meteorological Processor for Regulatory Models (MPRM) User's Guide. Publication No. EPA–454/B–96–002. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (NTIS No. PB 96–180518)

105. Paine, R.J., 1987. User's Guide to the CTDM Meteorological Preprocessor Program. Publication No. EPA–600/8–88–004. Office of Research & Development, Research Triangle Park, NC. (NTIS No. PB 88–162102)

106. Scire, J.S., F.R. Francoise, M.E. Fernau and R.J. Yamartino, 1998. A User's Guide for the CALMET Meteorological Model (Version 5.0). Earth Tech, Inc., Concord, MA. (*http://www.src.com/calpuff/calpuff1.htm*)

107. Environmental Protection Agency, 1984. Calms Processor (CALMPRO) User's Guide. Publication No. EPA–901/9–84–001. Office of Air Quality Planning & Standards, Region I, Boston, MA. (NTIS No. PB 84–229467)

108. Fox, D.G., 1984. Uncertainty in air quality modeling. *Bulletin of the American Meteorological Society*, 65(1): 27–36.

109. Burton, C.S., 1981. The Role of Atmospheric Models in Regulatory Decision-Making: Summary Report. Systems Applications, Inc., San Rafael, CA. Prepared under contract No. 68–01–5845 for U.S. Environmental Protection Agency, Research Triangle Park, NC. (Docket No. A–80–46, II–M–6)

110. Environmental Protection Agency, 1981. Proceedings of the Second Conference on Air Quality Modeling, Washington, DC. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (Docket No. A–80–46, II–M–16)

111. Hanna, S.R., 1989. Confidence limits for air quality model evaluations, as estimated by bootstrap and jackknife resampling methods. *Atmospheric Environment*, 23(6): 1385–1398.

112. Cox, W.M. and J.A. Tikvart, 1990. A statistical procedure for determining the best performing air quality simulation model. *Atmos. Environ.*, 24A(9): 2387–2395.

113. Oreskes, N.K., K. Shrader-Frechette and K. Beliz, 1994. Verification, validation and confirmation of numerical models in the earth sciences. *Science*, 263: 641–646.

114. Dekker, C.M., A. Groenendijk, C.J. Sliggers and G.K. Verboom, 1990. Quality Criteria for Models to Calculate Air Pollution. Lucht (Air) 90, Ministry of Housing, Physical Planning and Environment, Postbus 450, 2260 MB Leidschendam, The Netherlands; 52pp.

115. Weil, J.C., R.I. Sykes and A. Venkatram, 1992. Evaluating air-quality models: review and outlook. *Journal of Applied Meteorology*, 31: 1121–1145.

116. Cole, S.T. and P.J. Wicks, Editors (1995): Model Evaluation Group: Report of the Second Open Meeting. EUR 15990 EN, European Commission, Directorate-General XII, Environmental Research Programme, L–2920 Luxembourg; 77pp.

117. Hanna, S.R., 1982. Natural Variability of Observed Hourly SO_2 and CO Concentrations in St. Louis. *Atmospheric Environment*, 16(6): 1435–1440.

118. Bowne, N.E., 1981. Validation and Performance Criteria for Air Quality Models.

Appendix F in Air Quality Modeling and the Clean Air Act: Recommendations to EPA on Dispersion Modeling for Regulatory Applications. American Meteorological Society, Boston, MA; pp. 159–171. (Docket No. A–80–46, II–A–106)

119. Bowne, N.E. and R.J. Londergan, 1983. Overview, Results, and Conclusions for the EPRI Plume Model Validation and Development Project: Plains Site. EPRI EA–3074. Electric Power Research Institute, Palo Alto, CA.

120. Moore, G.E., T.E. Stoeckenius and D.A. Stewart, 1982. A Survey of Statistical Measures of Model Performance and Accuracy for Several Air Quality Models. Publication No. EPA–450/4–83–001. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (NTIS No. PB 83–260810)

121. Rhoads, R.G., 1981. Accuracy of Air Quality Models. Staff Report. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (Docket No. A–80–46, II–G–6)

122. Hanna, S.R., 1993. Uncertainties in air quality model predictions. *Boundary-Layer Meteorology*, 62: 3–20.

123. Pasquill, F., 1974. Atmospheric Diffusion, 2nd Edition. John Wiley and Sons, New York, NY; 479pp.

124. Morgan, M.G. and M. Henrion, 1990. Uncertainty, A Guide to Dealing With Uncertainty in Quantitative Risk and Policy Analysis. Cambridge University Press. New York, NY; 332pp.

125. Irwin, J.S., K. Steinberg, C. Hakkarinen and H. Feldman, 2001. Uncertainty in Air Quality Modeling for Risk Calculations. (CD–ROM) Proceedings of Guideline on Air Quality Models: A New Beginning. April 4–6, 2001, Newport, RI, Air & Waste Management Association. Pittsburgh, PA; 17pp.

126. Austin, B.S., T.E. Stoeckenius, M.C. Dudik and T.S. Stocking, 1988. User's Guide to the Expected Exceedances System. Systems Applications, Inc., San Rafael, CA. Prepared under Contract No. 68–02–4352 Option I for the U.S. Environmental Protection Agency, Research Triangle Park, NC. (Docket No. A–88–04, II–I–3)

127. Thrall, A.D., T.E. Stoeckenius and C.S. Burton, 1985. A Method for Calculating Dispersion Modeling Uncertainty Applied to the Regulation of an Emission Source. Systems Applications, Inc., San Rafael, CA. Prepared for the U.S. Environmental Protection Agency, Research Triangle Park, NC. (Docket No. A–80–46, IV–G–1)

128. ''Ten years of Harmonisation activities: Past, present and future'' at *http://www.dmu.dk/AtmosphericEnvironment/Harmoni/Conferences/Belgirate/BelgiratePapers.asp.*

129. ''A platform for model evaluation'' at *http://www.dmu.dk/AtmosphericEnvironment/Harmoni/Conferences/Belgirate/BelgiratePapers.asp.*

APPENDIX A TO APPENDIX W OF PART 51—SUMMARIES OF PREFERRED AIR QUALITY MODELS

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A.1 Aermod
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A.0 Introduction and Availability

(1) This appendix summarizes key features of refined air quality models preferred for specific regulatory applications. For each model, information is provided on availability, approximate cost (where applicable), regulatory use, data input, output format and options, simulation of atmospheric physics, and accuracy. These models may be used without a formal demonstration of applicability provided they satisfy the recommendations for regulatory use; not all options in the models are necessarily recommended for regulatory use.

(2) Many of these models have been subjected to a performance evaluation using comparisons with observed air quality data. Where possible, several of the models contained herein have been subjected to evaluation exercises, including (1) statistical performance tests recommended by the American Meteorological Society and (2) peer scientific reviews. The models in this appendix have been selected on the basis of the results of the model evaluations, experience with previous use, familiarity of the model to various air quality programs, and the costs and resource requirements for use.

(3) Codes and documentation for all models listed in this appendix are available from EPA's Support Center for Regulatory Air Models (SCRAM) Web site at *http://www.epa.gov/scram001.* Documentation is also available from the National Technical Information Service (NTIS), *http://www.ntis.gov* or U.S. Department of Commerce, Springfield, VA 22161; phone: (800) 553–6847. Where possible, accession numbers are provided.

A.1 AMS/EPA Regulatory Model—AERMOD

References

Environmental Protection Agency, 2004. AERMOD: Description of Model Formulation. Publication No. EPA–454/R–03–004. U.S. Environmental Protection Agency, Research Triangle Park, NC 27711; September 2004. (Available at *http://www.epa.gov/scram001/*)

Cimorelli, A. *et al.*, 2005. AERMOD: A Dispersion Model for Industrial Source Applications. Part I: General Model Formulation and Boundary Layer Characterization. *Journal of Applied Meteorology,* 44(5): 682–693.

Perry, S. *et al.*, 2005. AERMOD: A Dispersion Model for Industrial Source Applications. Part II: Model Performance against 17 Field Study Databases. *Journal of Applied Meteorology,* 44(5): 694–708.

Environmental Protection Agency, 2004. User's Guide for the AMS/EPA Regulatory Model—AERMOD. Publication No. EPA–454/B–03–001. U.S. Environmental Protection Agency, Research Triangle Park, NC 27711; September 2004. (Available at *http://www.epa.gov/scram001/*)

Environmental Protection Agency, 2004. User's Guide for the AERMOD Meteorological Preprocessor (AERMET). Publication No. EPA–454/B–03–002. U.S. Environmental Protection Agency, Research Triangle Park, NC 27711; November 2004. (Available at *http://www.epa.gov/scram001/*)

Environmental Protection Agency, 2004. User's Guide for the AERMOD Terrain Preprocessor (AERMAP). Publication No. EPA–454/B–03–003. U.S. Environmental Protection Agency, Research Triangle Park, NC 27711; October 2004. (Available at *http://www.epa.gov/scram001/*)

Schulman, L.L., D.G. Strimaitis and J.S. Scire, 2000. Development and evaluation of the PRIME plume rise and building downwash model. *Journal of the Air and Waste Management Association,* 50: 378–390.

Availability

The model codes and associated documentation are available on EPA's Internet SCRAM Web site (Section A.0).

Abstract

AERMOD is a steady-state plume dispersion model for assessment of pollutant concentrations from a variety of sources. AERMOD simulates transport and dispersion from multiple point, area, or volume sources based on an up-to-date characterization of the atmospheric boundary layer. Sources may be located in rural or urban areas, and receptors may be located in simple or complex terrain. AERMOD accounts for building wake effects (i.e., plume downwash) based on the PRIME building downwash algorithms. The model employs hourly sequential preprocessed meteorological data to estimate concentrations for averaging times from one hour to one year (also multiple years). AERMOD is designed to operate in concert with two pre-processor codes: AERMET processes meteorological data for input to AERMOD, and AERMAP processes terrain elevation data and generates receptor information for input to AERMOD.

a. Recommendations for Regulatory Use

(1) AERMOD is appropriate for the following applications:

- Point, volume, and area sources;
- Surface, near-surface, and elevated releases;
- Rural or urban areas;
- Simple and complex terrain;
- Transport distances over which steady-state assumptions are appropriate, up to 50km;
- 1-hour to annual averaging times; and
- Continuous toxic air emissions.

(2) For regulatory applications of AERMOD, the regulatory default option should be set, i.e., the parameter DFAULT should be employed in the MODELOPT record in the COntrol Pathway. The DFAULT option requires the use of terrain elevation data, stack-tip downwash, sequential date checking, and does not permit the use of the model in the SCREEN mode. In the regulatory default mode, pollutant half life or

decay options are not employed, except in the case of an urban source of sulfur dioxide where a four-hour half life is applied. Terrain elevation data from the U.S. Geological Survey 7.5-Minute Digital Elevation Model (*edcwww.cr.usgs.gov/doc/edchome/ndcdb/ndcdb.html*) or equivalent (approx. 30-meter resolution) should be used in all applications. In some cases, exceptions of the terrain data requirement may be made in consultation with the permit/SIP reviewing authority.

b. Input Requirements

(1) Source data: Required input includes source type, location, emission rate, stack height, stack inside diameter, stack gas exit velocity, stack gas temperature, area and volume source dimensions, and source elevation. Building dimensions and variable emission rates are optional.

(2) Meteorological data: The AERMET meteorological preprocessor requires input of surface characteristics, including surface roughness (zo), Bowen ratio, and albedo, as well as, hourly observations of wind speed between 7zo and 100m (reference wind speed measurement from which a vertical profile can be developed), wind direction, cloud cover, and temperature between zo and 100m (reference temperature measurement from which a vertical profile can be developed). Surface characteristics may be varied by wind sector and by season or month. A morning sounding (in National Weather Service format) from a representative upper air station, latitude, longitude, time zone, and wind speed threshold are also required in AERMET (instrument threshold is only required for site specific data). Additionally, measured profiles of wind, temperature, vertical and lateral turbulence may be required in certain applications (e.g., in complex terrain) to adequately represent the meteorology affecting plume transport and dispersion. Optionally, measurements of solar, or net radiation may be input to AERMET. Two files are produced by the AERMET meteorological preprocessor for input to the AERMOD dispersion model. The surface file contains observed and calculated surface variables, one record per hour. The profile file contains the observations made at each level of a meteorological tower (or remote sensor), or the one-level observations taken from other representative data (e.g., National Weather Service surface observations), one record per level per hour.

(i) Data used as input to AERMET should possess an adequate degree of representativeness to insure that the wind, temperature and turbulence profiles derived by AERMOD are both laterally and vertically representative of the source area. The adequacy of input data should be judged independently for each variable. The values for surface roughness, Bowen ratio, and albedo should reflect the surface characteristics in the vicinity of the meteorological tower, and should be adequately representative of the modeling domain. Finally, the primary atmospheric input variables including wind speed and direction, ambient temperature, cloud cover, and a morning upper air sounding should also be adequately representative of the source area.

(ii) For recommendations regarding the length of meteorological record needed to perform a regulatory analysis with AERMOD, see Section 8.3.1.

(3) Receptor data: Receptor coordinates, elevations, height above ground, and hill height scales are produced by the AERMAP terrain preprocessor for input to AERMOD. Discrete receptors and/or multiple receptor grids, Cartesian and/or polar, may be employed in AERMOD. AERMAP requires input of Digital Elevation Model (DEM) terrain data produced by the U.S. Geological Survey (USGS), or other equivalent data. AERMAP can be used optionally to estimate source elevations.

c. Output

Printed output options include input information, high concentration summary tables by receptor for user-specified averaging periods, maximum concentration summary tables, and concurrent values summarized by receptor for each day processed. Optional output files can be generated for: a listing of occurrences of exceedances of user-specified threshold value; a listing of concurrent (raw) results at each receptor for each hour modeled, suitable for post-processing; a listing of design values that can be imported into graphics software for plotting contours; an unformatted listing of raw results above a threshold value with a special structure for use with the TOXX model component of TOXST; a listing of concentrations by rank (e.g., for use in quantile-quantile plots); and, a listing of concentrations, including arc-maximum normalized concentrations, suitable for model evaluation studies.

d. Type of Model

AERMOD is a steady-state plume model, using Gaussian distributions in the vertical and horizontal for stable conditions, and in the horizontal for convective conditions. The vertical concentration distribution for convective conditions results from an assumed bi-Gaussian probability density function of the vertical velocity.

e. Pollutant Types

AERMOD is applicable to primary pollutants and continuous releases of toxic and hazardous waste pollutants. Chemical transformation is treated by simple exponential decay.

f. Source-Receptor Relationships

AERMOD applies user-specified locations for sources and receptors. Actual separation between each source-receptor pair is used. Source and receptor elevations are user input or are determined by AERMAP using USGS DEM terrain data. Receptors may be located at user-specified heights above ground level.

g. Plume Behavior

(1) In the convective boundary layer (CBL), the transport and dispersion of a plume is characterized as the superposition of three modeled plumes: The direct plume (from the stack), the indirect plume, and the penetrated plume, where the indirect plume accounts for the lofting of a buoyant plume near the top of the boundary layer, and the penetrated plume accounts for the portion of a plume that, due to its buoyancy, penetrates above the mixed layer, but can disperse downward and re-enter the mixed layer. In the CBL, plume rise is superposed on the displacements by random convective velocities (Weil *et al.*, 1997).

(2) In the stable boundary layer, plume rise is estimated using an iterative approach, similar to that in the CTDMPLUS model (see A.5 in this appendix).

(3) Stack-tip downwash and buoyancy induced dispersion effects are modeled. Building wake effects are simulated for stacks less than good engineering practice height using the methods contained in the PRIME downwash algorithms (Schulman, *et al.*, 2000). For plume rise affected by the presence of a building, the PRIME downwash algorithm uses a numerical solution of the mass, energy and momentum conservation laws (Zhang and Ghoniem, 1993). Streamline deflection and the position of the stack relative to the building affect plume trajectory and dispersion. Enhanced dispersion is based on the approach of Weil (1996). Plume mass captured by the cavity is well-mixed within the cavity. The captured plume mass is re-emitted to the far wake as a volume source.

(4) For elevated terrain, AERMOD incorporates the concept of the critical dividing streamline height, in which flow below this height remains horizontal, and flow above this height tends to rise up and over terrain (Snyder *et al.*, 1985). Plume concentration estimates are the weighted sum of these two limiting plume states. However, consistent with the steady-state assumption of uniform horizontal wind direction over the modeling domain, straight-line plume trajectories are assumed, with adjustment in the plume/receptor geometry used to account for the terrain effects.

h. Horizontal Winds

Vertical profiles of wind are calculated for each hour based on measurements and surface-layer similarity (scaling) relationships. At a given height above ground, for a given hour, winds are assumed constant over the modeling domain. The effect of the vertical variation in horizontal wind speed on dispersion is accounted for through simple averaging over the plume depth.

i. Vertical Wind Speed

In convective conditions, the effects of random vertical updraft and downdraft velocities are simulated with a bi-Gaussian probability density function. In both convective and stable conditions, the mean vertical wind speed is assumed equal to zero.

j. Horizontal Dispersion

Gaussian horizontal dispersion coefficients are estimated as continuous functions of the parameterized (or measured) ambient lateral turbulence and also account for buoyancy-induced and building wake-induced turbulence. Vertical profiles of lateral turbulence are developed from measurements and similarity (scaling) relationships. Effective turbulence values are determined from the portion of the vertical profile of lateral turbulence between the plume height and the receptor height. The effective lateral turbulence is then used to estimate horizontal dispersion.

k. Vertical Dispersion

In the stable boundary layer, Gaussian vertical dispersion coefficients are estimated as continuous functions of parameterized vertical turbulence. In the convective boundary layer, vertical dispersion is characterized by a bi-Gaussian probability density function, and is also estimated as a continuous function of parameterized vertical turbulence. Vertical turbulence profiles are developed from measurements and similarity (scaling) relationships. These turbulence profiles account for both convective and mechanical turbulence. Effective turbulence values are determined from the portion of the vertical profile of vertical turbulence between the plume height and the receptor height. The effective vertical turbulence is then used to estimate vertical dispersion.

l. Chemical Transformation

Chemical transformations are generally not treated by AERMOD. However, AERMOD does contain an option to treat chemical transformation using simple exponential decay, although this option is typically not used in regulatory applications, except for sources of sulfur dioxide in urban areas. Either a decay coefficient or a half life is input by the user. Note also that the Plume Volume Molar Ratio Method (subsection 5.1) and the Ozone Limiting Method (subsection 5.2.4) and for point-source NO_2 analyses are available as non-regulatory options.

m. Physical Removal

AERMOD can be used to treat dry and wet deposition for both gases and particles.

n. Evaluation Studies

American Petroleum Institute, 1998. Evaluation of State of the Science of Air Quality Dispersion Model, Scientific Evaluation, prepared by Woodward-Clyde Consultants, Lexington, Massachusetts, for American Petroleum Institute, Washington, D.C., 20005–4070.

Brode, R.W., 2002. Implementation and Evaluation of PRIME in AERMOD. Preprints of the 12th Joint Conference on Applications of Air Pollution Meteorology, May 20–24, 2002; American Meteorological Society, Boston, MA.

Brode, R.W., 2004. Implementation and Evaluation of Bulk Richardson Number Scheme in AERMOD. 13th Joint Conference on Applications of Air Pollution Meteorology, August 23–26, 2004; American Meteorological Society, Boston, MA.

Environmental Protection Agency, 2003. AERMOD: Latest Features and Evaluation Results. Publication No. EPA–454/R–03–003. U.S. Environmental Protection Agency, Research Triangle Park, NC. Available at *http://www.epa.gov/scram001/.*

A.2 Buoyant Line and Point Source Dispersion Model (BLP)

Reference

Schulman, Lloyd L., and Joseph S. Scire, 1980. Buoyant Line and Point Source (BLP) Dispersion Model User's Guide. Document P–7304B. Environmental Research and Technology, Inc., Concord, MA. (NTIS No. PB 81–164642; also available at *http://www.epa.gov/scram001/*)

Availability

The computer code is available on EPA's Internet SCRAM Web site and also on diskette (as PB 2002–500051) from the National Technical Information Service (see Section A.0).

Abstract

BLP is a Gaussian plume dispersion model designed to handle unique modeling problems associated with aluminum reduction plants, and other industrial sources where plume rise and downwash effects from stationary line sources are important.

a. Recommendations for Regulatory Use

(1) The BLP model is appropriate for the following applications:

- Aluminum reduction plants which contain buoyant, elevated line sources;
- Rural areas;
- Transport distances less than 50 kilometers;
- Simple terrain; and
- One hour to one year averaging times.

(2) The following options should be selected for regulatory applications:

(i) Rural (IRU=1) mixing height option;

(ii) Default (no selection) for plume rise wind shear (LSHEAR), transitional point source plume rise (LTRANS), vertical potential temperature gradient (DTHTA), vertical wind speed power law profile exponents (PEXP), maximum variation in number of stability classes per hour (IDELS), pollutant decay (DECFAC), the constant in Briggs' stable plume rise equation (CONST2), constant in Briggs' neutral plume rise equation (CONST3), convergence criterion for the line source calculations (CRIT), and maximum iterations allowed for line source calculations (MAXIT); and

(iii) Terrain option (TERAN) set equal to 0.0, 0.0, 0.0, 0.0, 0.0, 0.0

(3) For other applications, BLP can be used if it can be demonstrated to give the same estimates as a recommended model for the same application, and will subsequently be executed in that mode.

(4) BLP can be used on a case-by-case basis with specific options not available in a recommended model if it can be demonstrated, using the criteria in Section 3.2, that the model is more appropriate for a specific application.

b. Input Requirements

(1) Source data: point sources require stack location, elevation of stack base, physical stack height, stack inside diameter, stack gas exit velocity, stack gas exit temperature, and pollutant emission rate. Line sources require coordinates of the end points of the line, release height, emission rate, average line source width, average building width, average spacing between buildings, and average line source buoyancy parameter.

(2) Meteorological data: surface weather data from a preprocessor such as PCRAMMET which provides hourly stability class, wind direction, wind speed, temperature, and mixing height.

(3) Receptor data: locations and elevations of receptors, or location and size of receptor grid or request automatically generated receptor grid.

c. Output

(1) Printed output (from a separate post-processor program) includes:

(2) Total concentration or, optionally, source contribution analysis; monthly and annual frequency distributions for 1-, 3-, and 24-hour average concentrations; tables of 1-, 3-, and 24-hour average concentrations at each receptor; table of the annual (or length of run) average concentrations at each receptor;

(3) Five highest 1-, 3-, and 24-hour average concentrations at each receptor; and

(4) Fifty highest 1-, 3-, and 24-hour concentrations over the receptor field.

d. Type of Model

BLP is a gaussian plume model.

e. Pollutant Types

BLP may be used to model primary pollutants. This model does not treat settling and deposition.

f. Source-Receptor Relationship

(1) BLP treats up to 50 point sources, 10 parallel line sources, and 100 receptors arbitrarily located.

(2) User-input topographic elevation is applied for each stack and each receptor.

g. Plume Behavior

(1) BLP uses plume rise formulas of Schulman and Scire (1980).

(2) Vertical potential temperature gradients of 0.02 Kelvin per meter for E stability and 0.035 Kelvin per meter are used for stable plume rise calculations. An option for user input values is included.

(3) Transitional rise is used for line sources.

(4) Option to suppress the use of transitional plume rise for point sources is included.

(5) The building downwash algorithm of Schulman and Scire (1980) is used.

h. Horizontal Winds

(1) Constant, uniform (steady-state) wind is assumed for an hour.

Straight line plume transport is assumed to all downwind distances.

(2) Wind speeds profile exponents of 0.10, 0.15, 0.20, 0.25, 0.30, and 0.30 are used for stability classes A through F, respectively. An option for user-defined values and an option to suppress the use of the wind speed profile feature are included.

i. Vertical Wind Speed

Vertical wind speed is assumed equal to zero.

j. Horizontal Dispersion

(1) Rural dispersion coefficients are from Turner (1969), with no adjustment made for variations in surface roughness or averaging time.

(2) Six stability classes are used.

k. Vertical Dispersion

(1) Rural dispersion coefficients are from Turner (1969), with no adjustment made for variations in surface roughness.

(2) Six stability classes are used.

(3) Mixing height is accounted for with multiple reflections until the vertical plume standard deviation equals 1.6 times the

mixing height; uniform mixing is assumed beyond that point.

(4) Perfect reflection at the ground is assumed.

l. Chemical Transformation

Chemical transformations are treated using linear decay. Decay rate is input by the user.

m. Physical Removal

Physical removal is not explicitly treated.

n. Evaluation Studies

Schulman, L.L. and J.S. Scire, 1980. Buoyant Line and Point Source (BLP) Dispersion Model User's Guide, P–7304B. Environmental Research and Technology, Inc., Concord, MA.

Scire, J.S. and L.L. Schulman, 1981. Evaluation of the BLP and ISC Models with SF_6 Tracer Data and SO_2 Measurements at Aluminum Reduction Plants. APCA Specialty Conference on Dispersion Modeling for Complex Sources, St. Louis, MO.

A.3 CALINE3

Reference

Benson, Paul E., 1979. CALINE3—A Versatile Dispersion Model for Predicting Air Pollutant Levels Near Highways and Arterial Streets. Interim Report, Report Number FHWA/CA/TL–79/23. Federal Highway Administration, Washington, DC (NTIS No. PB 80–220841).

Availability

The CALINE3 model is available on diskette (as PB 95–502712) from NTIS. The source code and user's guide are also available on EPA's Internet SCRAM Web site (Section A.0).

Abstract

CALINE3 can be used to estimate the concentrations of nonreactive pollutants from highway traffic. This steady-state Gaussian model can be applied to determine air pollution concentrations at receptor locations downwind of ''at-grade,'' ''fill,'' ''bridge,'' and ''cut section'' highways located in relatively uncomplicated terrain. The model is applicable for any wind direction, highway orientation, and receptor location. The model has adjustments for averaging time and surface roughness, and can handle up to 20 links and 20 receptors. It also contains an algorithm for deposition and settling velocity so that particulate concentrations can be predicted.

a. Recommendations for Regulatory Use

CALINE–3 is appropriate for the following applications:

- Highway (line) sources;
- Urban or rural areas;
- Simple terrain;
- Transport distances less than 50 kilometers; and
- One-hour to 24-hour averaging times.

b. Input Requirements

(1) Source data: up to 20 highway links classed as ''at-grade,'' ''fill,'' ''bridge,'' or ''depressed''; coordinates of link end points; traffic volume; emission factor; source height; and mixing zone width.

(2) Meteorological data: wind speed, wind angle (measured in degrees clockwise from the Y axis), stability class, mixing height, ambient (background to the highway) concentration of pollutant.

(3) Receptor data: coordinates and height above ground for each receptor.

c. Output

Printed output includes concentration at each receptor for the specified meteorological condition.

d. Type of Model

CALINE–3 is a Gaussian plume model.

e. Pollutant Types

CALINE–3 may be used to model primary pollutants.

f. Source-Receptor Relationship

(1) Up to 20 highway links are treated.

(2) CALINE–3 applies user input location and emission rate for each link. User-input receptor locations are applied.

g. Plume Behavior

Plume rise is not treated.

h. Horizontal Winds

(1) User-input hourly wind speed and direction are applied.

(2) Constant, uniform (steady-state) wind is assumed for an hour.

i. Vertical Wind Speed

Vertical wind speed is assumed equal to zero.

j. Horizontal Dispersion

(1) Six stability classes are used.

(2) Rural dispersion coefficients from Turner (1969) are used, with adjustment for roughness length and averaging time.

(3) Initial traffic-induced dispersion is handled implicitly by plume size parameters.

k. Vertical Dispersion

(1) Six stability classes are used.

(2) Empirical dispersion coefficients from Benson (1979) are used including an adjustment for roughness length.

(3) Initial traffic-induced dispersion is handled implicitly by plume size parameters.

(4) Adjustment for averaging time is included.

l. Chemical Transformation

Not treated.

m. Physical Removal

Optional deposition calculations are included.

n. Evaluation Studies

Bemis, G.R. *et al.*, 1977. Air Pollution and Roadway Location, Design, and Operation—Project Overview. FHWA–CA–TL–7080–77–25, Federal Highway Administration, Washington, DC.

Cadle, S.H. *et al.*, 1976. Results of the General Motors Sulfate Dispersion Experiment, GMR–2107. General Motors Research Laboratories, Warren, MI.

Dabberdt, W.F., 1975. Studies of Air Quality on and Near Highways, Project 2761. Stanford Research Institute, Menlo Park, CA.

Environmental Protection Agency, 1986. Evaluation of Mobile Source Air Quality Simulation Models. EPA Publication No. EPA–450/4–86–002. Office of Air Quality Planning & Standards, Research Triangle Park, NC. (NTIS No. PB 86–167293)

A.4 CALPUFF

References

Scire, J.S., D.G. Strimaitis and R.J. Yamartino, 2000. A User's Guide for the CALPUFF Dispersion Model (Version 5.0). Earth Tech, Inc., Concord, MA.

Scire J.S., F.R. Robe, M.E. Fernau and R.J. Yamartino, 2000. A User's Guide for the CALMET Meteorological Model (Version 5.0). Earth Tech, Inc., Concord, MA.

Availability

The model code and its documentation are available at no cost for download from the model developers' Internet Web site: *http://www.src.com/calpuff/calpuff1.htm.* You may also contact Joseph Scire, Earth Tech, Inc., 196 Baker Avenue, Concord, MA 01742; Telephone: (978) 371–4270; Fax: (978) 371–2468; e-mail: *JScire@alum.mit.edu.*

Abstract

CALPUFF is a multi-layer, multi-species non-steady-state puff dispersion modeling system that simulates the effects of time- and space-varying meteorological conditions on pollutant transport, transformation, and removal. CALPUFF is intended for use on scales from tens of meters from a source to hundreds of kilometers. It includes algorithms for near-field effects such as stack tip downwash, building downwash, transitional buoyant and momentum plume rise, rain cap effects, partial plume penetration, subgrid scale terrain and coastal interactions effects, and terrain impingement as well as longer range effects such as pollutant removal due to wet scavenging and dry deposition, chemical transformation, vertical wind shear effects, overwater transport, plume fumigation, and visibility effects of particulate matter concentrations.

a. Recommendations for Regulatory Use

(1) CALPUFF is appropriate for long range transport (source-receptor distances of 50 to several hundred kilometers) of emissions from point, volume, area, and line sources. The meteorological input data should be fully characterized with time-and-space-varying three dimensional wind and meteorological conditions using CALMET, as discussed in paragraphs 8.3(d) and 8.3.1.2(d) of Appendix W.

(2) CALPUFF may also be used on a case-by-case basis if it can be demonstrated using the criteria in Section 3.2 that the model is more appropriate for the specific application. The purpose of choosing a modeling system like CALPUFF is to fully treat stagnation, wind reversals, and time and space variations of meteorological conditions on transport and dispersion, as discussed in paragraph 7.2.8(a).

(3) For regulatory applications of CALMET and CALPUFF, the regulatory default option should be used. Inevitably, some of the model control options will have to be set specific for the application using expert judgment and in consultation with the appropriate reviewing authorities.

b. Input Requirements

Source Data:

1. Point sources: Source location, stack height, diameter, exit velocity, exit temperature, base elevation, wind direction specific building dimensions (for building downwash calculations), and emission rates for each pollutant. Particle size distributions may be entered for particulate matter. Temporal emission factors (diurnal cycle, monthly cycle, hour/season, wind speed/stability class, or temperature-dependent emission factors) may also be entered. Arbitrarily-varying point source parameters may be entered from an external file.

2. Area sources: Source location and shape, release height, base elevation, initial vertical distribution (σ_z) and emission rates for each pollutant. Particle size distributions may be entered for particulate matter. Temporal emission factors (diurnal cycle, monthly cycle, hour/season, wind speed/stability class, or temperature-dependent emission factors) may also be entered. Arbitrarily-varying area source parameters may be entered from an external file. Area sources specified in the external file are allowed to be buoyant and their location, size, shape, and other source characteristics are allowed to change in time.

3. Volume sources: Source location, release height, base elevation, initial horizontal and vertical distributions (σ_y, σ_z) and emission rates for each pollutant. Particle size distributions may be entered for particulate matter. Temporal emission factors (diurnal cycle, monthly cycle, hour/season, wind speed/stability class, or temperature-dependent emission factors) may also be entered. Arbitrarily-varying volume source parameters may be entered from an external file. Volume sources with buoyancy can be simulated by treating the source as a point source and entering initial plume size parameters—initial (σ_y, σ_z)—to define the initial size of the volume source.

4. Line sources: Source location, release height, base elevation, average buoyancy parameter, and emission rates for each pollutant. Building data may be entered for line source emissions experiencing building downwash effects. Particle size distributions may be entered for particulate matter. Temporal emission factors (diurnal cycle, monthly cycle, hour/season, wind speed/stability class, or temperature-dependent emission factors) may also be entered. Arbitrarily-varying line source parameters may be entered from an external file.

Meteorological Data (different forms of meteorological input can be used by CALPUFF):

1. Time-dependent three-dimensional (3–D) meteorological fields generated by CALMET. This is the preferred mode for running CALPUFF. Data inputs used by CALMET include surface observations of wind speed, wind direction, temperature, cloud cover, ceiling height, relative humidity, surface pressure, and precipitation (type and amount), and upper air sounding data (wind speed, wind direction, temperature, and height) and air-sea temperature differences (over water). Optional 3–D meteorological prognostic model output (e.g., from models such as MM5, RUC, Eta and RAMS) can be used by CALMET as well (paragraph 8.3.1.2(d)). CALMET contains an option to be run in ''No-observations'' mode (Robe et al., 2002), which allows the 3–D CALMET meteorological fields to be based on prognostic model output alone, without observations. This allows CALMET and CALPUFF to be run in prognostic mode for forecast applications.

2. Single station surface and upper air meteorological data in CTDMPLUS data file formats (SURFACE.DAT and PROFILE.DAT files) or AERMOD data file formats. These options allow a vertical variation in the meteorological parameters but no horizontal spatial variability.

3. Single station meteorological data in ISCST3 data file format. This option does not account for variability of the meteorological parameters in the horizontal or vertical, except as provided for by the use of stability-dependent wind shear exponents and average temperature lapse rates.

Gridded terrain and land use data are required as input into CALMET when Option 1 is used. Geophysical processor programs are provided that interface the modeling system to standard terrain and land use data bases available from various sources such as the U.S. Geological Survey (USGS) and the National Aeronautics and Space Administration (NASA).

Receptor Data:

CALPUFF includes options for gridded and non-gridded (discrete) receptors. Special subgrid-scale receptors are used with the subgrid-scale complex terrain option. An option is provided for discrete receptors to be placed at ground-level or above the local ground level (i.e., flagpole receptors). Gridded and subgrid-scale receptors are placed at the local ground level only.

Other Input:

CALPUFF accepts hourly observations of ozone concentrations for use in its chemical transformation algorithm. Monthly concentrations of ammonia concentrations can be specified in the CALPUFF input file, although higher time-resolution ammonia variability can be computed using the POSTUTIL program. Subgrid-scale coastlines can be specified in its coastal boundary file. Optional, user-specified deposition velocities and chemical transformation rates can also be entered. CALPUFF accepts the CTDMPLUS terrain and receptor files for use in its subgrid-scale terrain algorithm. Inflow boundary conditions of modeled pollutants can be specified in a boundary condition file. Liquid water content variables including cloud water/ice and precipitation water/ice can be used as input for visibility analyses and other CALPUFF modules.

c. Output

CALPUFF produces files of hourly concentrations of ambient concentrations for each modeled species, wet deposition fluxes, dry deposition fluxes, and for visibility applications, extinction coefficients. Postprocessing programs (PRTMET, CALPOST, CALSUM, APPEND, and POSTUTIL) provide options for summing, scaling, analyzing and displaying the modeling results. CALPOST contains options for computing of light extinction (visibility) and POSTUTIL allows the re-partitioning of nitric acid and nitrate to account for the effects of ammonia limitation (Scire *et al.*, 2001; Escoffier-Czaja and Scire, 2002). CALPUFF contains an options to output liquid water concentrations for use in computing visible plume lengths and frequency of icing and fogging from cooling towers and other water vapor sources. The CALPRO Graphical User Interface (GUI) contains options for creating graphics such as contour plots, vector plots and other displays when linked to graphics software.

d. Type of Model

(1) CALPUFF is a non-steady-state time- and space-dependent Gaussian puff model. CALPUFF treats primary pollutants and simulates secondary pollutant formation using a parameterized, quasi-linear chemical conversion mechanism. Pollutants treated include SO_2, $SO_4^{=}$, NO_X (i.e., NO + NO_2), HNO_3, NO_3^-, NH_3, PM–10, PM–2.5, toxic pollutants and others pollutant species that are either inert or subject to quasi-linear chemical reactions. The model includes a resistance-based dry deposition model for both gaseous pollutants and particulate matter. Wet deposition is treated using a scavenging coefficient approach. The model has detailed parameterizations of complex terrain effects, including terrain impingement, side-wall scrapping, and steep-walled terrain influences on lateral plume growth. A subgrid-scale complex terrain module based on a dividing streamline concept divides the flow into a lift component traveling over the obstacle and a wrap component deflected around the obstacle.

(2) The meteorological fields used by CALPUFF are produced by the CALMET meteorological model. CALMET includes a diagnostic wind field model containing parameterized treatments of slope flows, valley flows, terrain blocking effects, and kinematic terrain effects, lake and sea breeze circulations, a divergence minimization procedure, and objective analysis of observational data. An energy-balance scheme is used to compute sensible and latent heat fluxes and turbulence parameters over land surfaces. A profile method is used over water. CALMET contains interfaces to prognostic meteorological models such as the Penn State/NCAR Mesoscale Model (e.g., MM5; Section 12.0, ref. 86), as well as the RAMS, Ruc and Eta models.

e. Pollutant Types

CALPUFF may be used to model gaseous pollutants or particulate matter that are inert or which undergo quasi-linear chemical reactions, such as SO_2, SO_4 =, NO_X (*i.e.*, NO + NO_2), HNO_3, NO_3-, NH_3, PM–10, PM–2.5 and toxic pollutants. For regional haze analyses, sulfate and nitrate particulate components are explicitly treated.

f. Source-Receptor Relationships

CALPUFF contains no fundamental limitations on the number of sources or receptors. Parameter files are provided that allow the user to specify the maximum number of sources, receptors, puffs, species, grid cells, vertical layers, and other model parameters. Its algorithms are designed to be suitable for source-receptor distances from tens of meters to hundreds of kilometers.

g. Plume Behavior

Momentum and buoyant plume rise is treated according to the plume rise equations of Briggs (1975) for non-downwashing point sources, Schulman and Scire (1980) for line sources and point sources subject to building downwash effects using the Schulman-Scire downwash algorithm, and Zhang (1993) for buoyant area sources and point sources affected by building downwash when using the PRIME building downwash method. Stack tip downwash effects and partial plume penetration into elevated temperature inversions are included. An algorithm to treat horizontally-oriented vents and stacks with rain caps is included.

h. Horizontal Winds

A three-dimensional wind field is computed by the CALMET meteorological model. CALMET combines an objective analysis procedure using wind observations with parameterized treatments of slope flows, valley flows, terrain kinematic effects, terrain blocking effects, and sea/lake breeze circulations. CALPUFF may optionally use single station (horizontally-constant) wind fields in the CTDMPLUS, AERMOD or ISCST3 data formats.

i. Vertical Wind Speed

Vertical wind speeds are not used explicitly by CALPUFF. Vertical winds are used in the development of the horizontal wind components by CALMET.

j. Horizontal Dispersion

Turbulence-based dispersion coefficients provide estimates of horizontal plume dispersion based on measured or computed values of σ_v. The effects of building downwash and buoyancy-induced dispersion are included. The effects of vertical wind shear are included through the puff splitting algorithm. Options are provided to use Pasquill-Gifford (rural) and McElroy-Pooler (urban) dispersion coefficients. Initial plume size from area or volume sources is allowed.

k. Vertical Dispersion

Turbulence-based dispersion coefficients provide estimates of vertical plume dispersion based on measured or computed values of σ_w. The effects of building downwash and buoyancy-induced dispersion are included. Vertical dispersion during convective conditions is simulated with a probability density function (pdf) model based on Weil *et al.* (1997). Options are provided to use Pasquill-Gifford (rural) and McElroy-Pooler (urban) dispersion coefficients. Initial plume size from area or volume sources is allowed.

l. Chemical Transformation

Gas phase chemical transformations are treated using parameterized models of SO_2 conversion to SO_4= and NO conversion to NO_3-, HNO_3, and NO_2. Organic aerosol formation is treated. The POSTUTIL program contains an option to re-partition HNO_3 and NO_3- in order to treat the effects of ammonia limitation.

m. Physical Removal

Dry deposition of gaseous pollutants and particulate matter is parameterized in terms of a resistance-based deposition model. Gravitational settling, inertial impaction, and Brownian motion effects on deposition of particulate matter is included. CALPUFF contains an option to evaluate the effects of plume tilt resulting from gravitational settling. Wet deposition of gases and particulate matter is parameterized in terms of a scavenging coefficient approach.

n. Evaluation Studies

Berman, S., J.Y. Ku, J. Zhang and S.T. Rao, 1977. Uncertainties in estimating the mixing depth—Comparing three mixing depth models with profiler measurements, *Atmospheric Environment,* 31: 3023–3039.

Chang, J.C., P. Franzese, K. Chayantrakom and S.R. Hanna, 2001. Evaluations of CALPUFF, HPAC and VLSTRACK with Two Mesoscale Field Datasets. *Journal of Applied Meteorology,* 42(4): 453–466.

Environmental Protection Agency, 1998. Interagency Workgroup on Air Quality Modeling (IWAQM) Phase 2 Summary Report and Recommendations for Modeling Long-Range Transport Impacts. EPA Publication No. EPA–454/R–98–019. Office of Air Quality Planning & Standards, Research Triangle Park, NC.

Irwin, J.S., 1997. A Comparison of CALPUFF Modeling Results with 1997 INEL Field Data Results. In *Air Pollution Modeling and its Application, XII.* Edited by S.E. Gyrning and N. Chaumerliac. Plenum Press, New York, NY.

Irwin, J.S., J.S. Scire and D.G. Strimaitis, 1996. A Comparison of CALPUFF Modeling Results with CAPTEX Field Data Results. In *Air Pollution Modeling and its Application, XI.* Edited by S.E. Gyrning and F.A. Schiermeier. Plenum Press, New York, NY.

Morrison, K, Z–X Wu, J.S. Scire, J. Chenier and T. Jeffs-Schonewille, 2003. CALPUFF-Based Predictive and Reactive Emission Control System. 96th A&WMA Annual Conference & Exhibition, 22–26 June 2003; San Diego, CA.

Schulman, L.L., D.G. Strimaitis and J.S. Scire, 2000. Development and evaluation of the PRIME Plume Rise and Building Downwash Model. JAWMA, 50: 378–390.

Scire, J.S., Z–X Wu, D.G. Strimaitis and G.E. Moore, 2001. The Southwest Wyoming Regional CALPUFF Air Quality Modeling Study—Volume I. Prepared for the Wyoming Dept. of Environmental Quality. Available from Earth Tech at *http://www.src.com.*

Strimaitis, D.G., J.S. Scire and J.C. Chang, 1998. Evaluation of the CALPUFF Dispersion Model with Two Power Plant Data Sets. Tenth Joint Conference on the Application of Air Pollution Meteorology, Phoenix, Arizona. American Meteorological Society, Boston, MA. January 11–16, 1998.

A.5 Complex Terrain Dispersion Model Plus Algorithms for Unstable Situations (CTDMPLUS)

Reference

Perry, S.G., D.J. Burns, L.H. Adams, R.J. Paine, M.G. Dennis, M.T. Mills, D.G. Strimaitis, R.J. Yamartino and E.M. Insley, 1989. User's Guide to the Complex Terrain Dispersion Model Plus Algorithms for Unstable Situations (CTDMPLUS). Volume 1: Model Descriptions and User Instructions. EPA Publication No. EPA–600/8–89–041. Environmental Protection Agency, Research Triangle Park, NC. (NTIS No. PB 89–181424)

Perry, S.G., 1992. CTDMPLUS: A Dispersion Model for Sources near Complex Topography. Part I: Technical Formulations. *Journal of Applied Meteorology,* 31(7): 633–645.

Availability

This model code is available on EPA's Internet SCRAM Web site and also on diskette (as PB 90–504119) from the National Technical Information Service (Section A.0).

Abstract

CTDMPLUS is a refined point source Gaussian air quality model for use in all stability conditions for complex terrain applications. The model contains, in its entirety, the technology of CTDM for stable and neutral conditions. However, CTDMPLUS can also simulate daytime, unstable conditions, and has a number of additional capabilities for improved user friendliness. Its use of meteorological data and terrain information is different from other EPA models; considerable detail for both types of input data is required and is supplied by preprocessors specifically designed for CTDMPLUS. CTDMPLUS requires the parameterization of individual hill shapes using the terrain preprocessor and the association of each model receptor with a particular hill.

a. Recommendation for Regulatory Use

CTDMPLUS is appropriate for the following applications:

- Elevated point sources;
- Terrain elevations above stack top;
- Rural or urban areas;
- Transport distances less than 50 kilometers; and
- One hour to annual averaging times when used with a post-processor program such as CHAVG.

b. Input Requirements

(1) Source data: For each source, user supplies source location, height, stack diameter, stack exit velocity, stack exit temperature, and emission rate; if variable emissions are appropriate, the user supplies hourly values for emission rate, stack exit velocity, and stack exit temperature.

(2) Meteorological data: For applications of CTDMPLUS, multiple level (typically three or more) measurements of wind speed and direction, temperature and turbulence (wind fluctuation statistics) are required to create the basic meteorological data file (''PROFILE''). Such measurements should be obtained up to the representative plume height(s) of interest (*i.e.*, the plume height(s) under those conditions important to the determination of the design concentration). The representative plume height(s) of interest should be determined using an appropriate complex terrain screening procedure (*e.g.*, CTSCREEN) and should be documented in the monitoring/modeling protocol. The necessary meteorological measurements should be obtained from an appropriately

sited meteorological tower augmented by SODAR and/or RASS if the representative plume height(s) of interest is above the levels represented by the tower measurements. Meteorological preprocessors then create a SURFACE data file (hourly values of mixed layer heights, surface friction velocity, Monin-Obukhov length and surface roughness length) and a RAWINsonde data file (upper air measurements of pressure, temperature, wind direction, and wind speed).

(3) Receptor data: receptor names (up to 400) and coordinates, and hill number (each receptor must have a hill number assigned).

(4) Terrain data: user inputs digitized contour information to the terrain preprocessor which creates the TERRAIN data file (for up to 25 hills).

c. Output

(1) When CTDMPLUS is run, it produces a concentration file, in either binary or text format (user's choice), and a list file containing a verification of model inputs, *i.e.*,

- Input meteorological data from ''SURFACE'' and ''PROFILE''.
- Stack data for each source.
- Terrain information.
- Receptor information.
- Source-receptor location (line printer map).

(2) In addition, if the case-study option is selected, the listing includes:

- Meteorological variables at plume height.
- Geometrical relationships between the source and the hill.
- Plume characteristics at each receptor, *i.e.*,

—Distance in along-flow and cross flow direction
—Effective plume-receptor height difference
—Effective σ_y & σ_z values, both flat terrain and hill induced (the difference shows the effect of the hill)
—Concentration components due to WRAP, LIFT and FLAT.

(3) If the user selects the TOPN option, a summary table of the top 4 concentrations at each receptor is given. If the ISOR option is selected, a source contribution table for every hour will be printed.

(4) A separate disk file of predicted (1-hour only) concentrations (''CONC'') is written if the user chooses this option. Three forms of output are possible:

(i) A binary file of concentrations, one value for each receptor in the hourly sequence as run;

(ii) A text file of concentrations, one value for each receptor in the hourly sequence as run; or

(iii) A text file as described above, but with a listing of receptor information (names, positions, hill number) at the beginning of the file.

(3) Hourly information provided to these files besides the concentrations themselves includes the year, month, day, and hour information as well as the receptor number with the highest concentration.

d. Type of Model

CTDMPLUS is a refined steady-state, point source plume model for use in all stability conditions for complex terrain applications.

e. Pollutant Types

CTDMPLUS may be used to model non-reactive, primary pollutants.

f. Source-Receptor Relationship

Up to 40 point sources, 400 receptors and 25 hills may be used. Receptors and sources are allowed at any location. Hill slopes are assumed not to exceed 15°, so that the linearized equation of motion for Boussinesq flow are applicable. Receptors upwind of the impingement point, or those associated with any of the hills in the modeling domain, require separate treatment.

g. Plume Behavior

(1) As in CTDM, the basic plume rise algorithms are based on Briggs' (1975) recommendations.

(2) A central feature of CTDMPLUS for neutral/stable conditions is its use of a critical dividing-streamline height (H_c) to separate the flow in the vicinity of a hill into two separate layers. The plume component in the upper layer has sufficient kinetic energy to pass over the top of the hill while streamlines in the lower portion are constrained to flow in a horizontal plane around the hill. Two separate components of CTDMPLUS compute ground-level concentrations resulting from plume material in each of these flows.

(3) The model calculates on an hourly (or appropriate steady averaging period) basis how the plume trajectory (and, in stable/neutral conditions, the shape) is deformed by each hill. Hourly profiles of wind and temperature measurements are used by CTDMPLUS to compute plume rise, plume penetration (a formulation is included to handle penetration into elevated stable layers, based on Briggs (1984)), convective scaling parameters, the value of H_c, and the Froude number above H_c.

h. Horizontal Winds

CTDMPLUS does not simulate calm meteorological conditions. Both scalar and vector wind speed observations can be read by the model. If vector wind speed is unavailable, it is calculated from the scalar wind speed. The assignment of wind speed (either vector or scalar) at plume height is done by either:

- Interpolating between observations above and below the plume height, or
- Extrapolating (within the surface layer) from the nearest measurement height to the plume height.

i. Vertical Wind Speed

Vertical flow is treated for the plume component above the critical dividing streamline height (H_c); see ''Plume Behavior''.

j. Horizontal Dispersion

Horizontal dispersion for stable/neutral conditions is related to the turbulence velocity scale for lateral fluctuations, σ_v, for which a minimum value of 0.2 m/s is used. Convective scaling formulations are used to estimate horizontal dispersion for unstable conditions.

k. Vertical Dispersion

Direct estimates of vertical dispersion for stable/neutral conditions are based on observed vertical turbulence intensity, *e.g.*, σ_w (standard deviation of the vertical velocity fluctuation). In simulating unstable (convective) conditions, CTDMPLUS relies on a skewed, bi-Gaussian probability density function (pdf) description of the vertical velocities to estimate the vertical distribution of pollutant concentration.

l. Chemical Transformation

Chemical transformation is not treated by CTDMPLUS.

m. Physical Removal

Physical removal is not treated by CTDMPLUS (complete reflection at the ground/hill surface is assumed).

n. Evaluation Studies

Burns, D.J., L.H. Adams and S.G. Perry, 1990. Testing and Evaluation of the CTDMPLUS Dispersion Model: Daytime Convective Conditions. Environmental Protection Agency, Research Triangle Park, NC.

Paumier, J.O., S.G. Perry and D.J. Burns, 1990. An Analysis of CTDMPLUS Model Predictions with the Lovett Power Plant Data Base. Environmental Protection Agency, Research Triangle Park, NC.

Paumier, J.O., S.G. Perry and D.J. Burns, 1992. CTDMPLUS: A Dispersion Model for Sources near Complex Topography. Part II: Performance Characteristics. *Journal of Applied Meteorology,* 31(7): 646–660.

A.6 Offshore and Coastal Dispersion Model (OCD)

Reference

DiCristofaro, D.C. and S.R. Hanna, 1989. OCD: The Offshore and Coastal Dispersion Model, Version 4. Volume I: User's Guide, and Volume II: Appendices. Sigma Research Corporation, Westford, MA. (NTIS Nos. PB 93–144384 and PB 93–144392; also available at *http://www.epa.gov/scram001/*)

Availability

This model code is available on EPA's Internet SCRAM Web site and also on diskette (as PB 91–505230) from the National Technical Information Service (see Section A.0). Official contact at Minerals Management Service: Mr. Dirk Herkhof, Parkway Atrium Building, 381 Elden Street, Herndon, VA 20170, Phone: (703) 787–1735.

Abstract

(1) OCD is a straight-line Gaussian model developed to determine the impact of offshore emissions from point, area or line sources on the air quality of coastal regions. OCD incorporates overwater plume transport and dispersion as well as changes that occur as the plume crosses the shoreline. Hourly meteorological data are needed from both offshore and onshore locations. These include water surface temperature, overwater air temperature, mixing height, and relative humidity.

(2) Some of the key features include platform building downwash, partial plume penetration into elevated inversions, direct use of turbulence intensities for plume dispersion, interaction with the overland internal boundary layer, and continuous shoreline fumigation.

a. Recommendations for Regulatory Use

OCD has been recommended for use by the Minerals Management Service for emissions located on the Outer Continental Shelf (50 FR 12248; 28 March 1985). OCD is applicable for overwater sources where onshore receptors are below the lowest source height. Where onshore receptors are above the lowest source height, offshore plume transport and dispersion may be modeled on a case-by-case basis in consultation with the appropriate reviewing authority (paragraph 3.0(b)).

b. Input Requirements

(1) Source data: Point, area or line source location, pollutant emission rate, building height, stack height, stack gas temperature, stack inside diameter, stack gas exit velocity, stack angle from vertical, elevation of stack base above water surface and gridded specification of the land/water surfaces. As an option, emission rate, stack gas exit velocity and temperature can be varied hourly.

(2) Meteorological data (over water): Wind direction, wind speed, mixing height, relative humidity, air temperature, water surface temperature, vertical wind direction shear (optional), vertical temperature gradient (optional), turbulence intensities (optional).

(2) Meteorological data:

Over land: Surface weather data from a preprocessor such as PCRAMMET which provides hourly stability class, wind direction, wind speed, ambient temperature, and mixing height are required.

Over water: Hourly values for mixing height, relative humidity, air temperature, and water surface temperature are required; if wind speed/direction are missing, values over land will be used (if available); vertical wind direction shear, vertical temperature gradient, and turbulence intensities are optional.

(3) Receptor data: Location, height above local ground-level, ground-level elevation above the water surface.

c. Output

(1) All input options, specification of sources, receptors and land/water map including locations of sources and receptors.

(2) Summary tables of five highest concentrations at each receptor for each averaging period, and average concentration for entire run period at each receptor.

(3) Optional case study printout with hourly plume and receptor characteristics. Optional table of annual impact assessment from non-permanent activities.

(4) Concentration files written to disk or tape can be used by ANALYSIS postprocessor to produce the highest concentrations for each receptor, the cumulative frequency distributions for each receptor, the tabulation of all concentrations exceeding a given threshold, and the manipulation of hourly concentration files.

d. Type of Model

OCD is a Gaussian plume model constructed on the framework of the MPTER model.

e. Pollutant Types

OCD may be used to model primary pollutants. Settling and deposition are not treated.

f. Source-Receptor Relationship

(1) Up to 250 point sources, 5 area sources, or 1 line source and 180 receptors may be used.

(2) Receptors and sources are allowed at any location.

(3) The coastal configuration is determined by a grid of up to 3600 rectangles. Each element of the grid is designated as either land or water to identify the coastline.

g. Plume Behavior

(1) As in ISC, the basic plume rise algorithms are based on Briggs' recommendations.

(2) Momentum rise includes consideration of the stack angle from the vertical.

(3) The effect of drilling platforms, ships, or any overwater obstructions near the source are used to decrease plume rise using a revised platform downwash algorithm based on laboratory experiments.

(4) Partial plume penetration of elevated inversions is included using the suggestions of Briggs (1975) and Weil and Brower (1984).

(5) Continuous shoreline fumigation is parameterized using the Turner method where complete vertical mixing through the thermal internal boundary layer (TIBL) occurs as soon as the plume intercepts the TIBL.

h. Horizontal Winds

(1) Constant, uniform wind is assumed for each hour.

(2) Overwater wind speed can be estimated from overland wind speed using relationship of Hsu (1981).

(3) Wind speed profiles are estimated using similarity theory (Businger, 1973). Surface layer fluxes for these formulas are calculated from bulk aerodynamic methods.

i. Vertical Wind Speed

Vertical wind speed is assumed equal to zero.

j. Horizontal Dispersion

(1) Lateral turbulence intensity is recommended as a direct estimate of horizontal dispersion. If lateral turbulence intensity is not available, it is estimated from boundary layer theory. For wind speeds less than 8 m/s, lateral turbulence intensity is assumed inversely proportional to wind speed.

(2) Horizontal dispersion may be enhanced because of obstructions near the source. A virtual source technique is used to simulate the initial plume dilution due to downwash.

(3) Formulas recommended by Pasquill (1976) are used to calculate buoyant plume enhancement and wind direction shear enhancement.

(4) At the water/land interface, the change to overland dispersion rates is modeled using a virtual source. The overland dispersion rates can be calculated from either lateral turbulence intensity or Pasquill-Gifford curves. The change is implemented where the plume intercepts the rising internal boundary layer.

k. Vertical Dispersion

(1) Observed vertical turbulence intensity is not recommended as a direct estimate of vertical dispersion. Turbulence intensity should be estimated from boundary layer theory as default in the model. For very stable conditions, vertical dispersion is also a function of lapse rate.

(2) Vertical dispersion may be enhanced because of obstructions near the source. A virtual source technique is used to simulate the initial plume dilution due to downwash.

(3) Formulas recommended by Pasquill (1976) are used to calculate buoyant plume enhancement.

(4) At the water/land interface, the change to overland dispersion rates is modeled using a virtual source. The overland dispersion rates can be calculated from either vertical turbulence intensity or the Pasquill-Gifford coefficients. The change is implemented where the plume intercepts the rising internal boundary layer.

1. Chemical Transformation

Chemical transformations are treated using exponential decay. Different rates can be specified by month and by day or night.

m. Physical Removal

Physical removal is also treated using exponential decay.

n. Evaluation Studies

DiCristofaro, D.C. and S.R. Hanna, 1989. OCD: The Offshore and Coastal Dispersion Model. Volume I: User's Guide. Sigma Research Corporation, Westford, MA.

Hanna, S.R., L.L. Schulman, R.J. Paine and J.E. Pleim, 1984. The Offshore and Coastal Dispersion (OCD) Model User's Guide, Revised. OCS Study, MMS 84–0069. Environmental Research & Technology, Inc., Concord, MA. (NTIS No. PB 86–159803).

Hanna, S.R., L.L. Schulman, R.J. Paine, J.E. Pleim and M. Baer, 1985. Development and Evaluation of the Offshore and Coastal Dispersion (OCD) Model. *Journal of the Air Pollution Control Association,* 35: 1039–1047.

Hanna, S.R. and D.C. DiCristofaro, 1988. Development and Evaluation of the OCD/API Model. Final Report, API Pub. 4461, American Petroleum Institute, Washington, DC.

A. REFERENCES

Benson, P.E., 1979. CALINE3—A Versatile Dispersion Model for Predicting Air Pollution Levels Near Highways and Arterial Streets. Interim Report, Report Number FHWA/CA/TL–79/23. Federal Highway Administration, Washington, DC.

Briggs, G.A., 1975. Plume Rise Predictions. Lectures on Air Pollution and Environmental Impact Analyses. American Meteorological Society, Boston, MA, pp. 59–111.

Briggs, G.A., 1984. Analytical Parameterizations of Diffusion: The Convective Boundary Layer. *Journal of Climate and Applied Meteorology,* 24(11): 1167–1186.

Environmental Protection Agency, 1980. Recommendations on Modeling (October 1980 Meetings). Appendix G to: Summary of Comments and Responses on the October 1980 Proposed Revisions to the Guideline on Air Quality Models. Meteorology and Assessment Division, Office of Research and Development, Research Triangle Park, NC 27711.

Environmental Protection Agency, 1998. Interagency Workgroup on Air Quality

Modeling (IWAQM) Phase 2 Summary Report and Recommendations for Modeling Long-Range Transport Impacts. Publication No. EPA–454/R–98–019. (NTIS No. PB 99–121089).

Escoffier-Czaja, C. and J.S. Scire, 2002. The Effects of Ammonia Limitation on Nitrate Aerosol Formation and Visibility Impacts in Class I Areas. Twelfth AMS/AWMA Conference on the Application of Air Pollution Meteorology, 20–24 May 2002; Norfolk, VA.

Gifford, F.A., Jr. 1976. Turbulent Diffusion Typing Schemes—A Review. *Nuclear Safety,* 17: 68–86.

Horst, T.W., 1983. A Correction to the Gaussian Source-depletion Model. In *Precipitation Scavenging, Dry Deposition and Resuspension*. H. R. Pruppacher, R.G. Semonin and W.G.N. Slinn, eds., Elsevier, NY.

Hsu, S.A., 1981. Models for Estimating Offshore Winds from Onshore Meteorological Measurements. *Boundary Layer Meteorology,* 20: 341–352.

Huber, A.H. and W.H. Snyder, 1976. Building Wake Effects on Short Stack Effluents. Third Symposium on Atmospheric Turbulence, Diffusion and Air Quality, American Meteorological Society, Boston, MA.

Irwin, J.S., 1979. A Theoretical Variation of the Wind Profile Power-Law Exponent as a Function of Surface Roughness and Stability. *Atmospheric Environment,* 13: 191–194.

Liu, M.K. *et al.*, 1976. The Chemistry, Dispersion, and Transport of Air Pollutants Emitted from Fossil Fuel Power Plants in California: Data Analysis and Emission Impact Model. Systems Applications, Inc., San Rafael, CA.

Pasquill, F., 1976. Atmospheric Dispersion Parameters in Gaussian Plume Modeling Part II. Possible Requirements for Change in the Turner Workbook Values. Publication No. EPA–600/4–76–030b. Office of Air Quality Planning & Standards, Research Triangle Park, NC 27711.

Petersen, W.B., 1980. User's Guide for HIWAY–2 A Highway Air Pollution Model. Publication No. EPA–600/8–80–018. Office of Research & Development, Research Triangle Park, NC 27711. (NTIS PB 80–227556)

Rao, T.R. and M.T. Keenan, 1980. Suggestions for Improvement of the EPA–HIWAY Model. *Journal of the Air Pollution Control Association,* 30: 247–256 (and reprinted as Appendix C in Petersen, 1980).

Robe, F.R., Z–X. Wu and J.S. Scire, 2002: Real-time SO_2 Forecasting System with Combined ETA Analysis and CALPUFF Modeling. Proceedings of the 8th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes, 14–17 October 2002; Sofia, Bulgaria.

Schulman, L.L. and J.S. Scire, 1980: Buoyant Line and Point Source (BLP) dispersion model user's guide. The Aluminum Association; Washington, DC. (*See* A.2 in this appendix.)

Schulman, L.L. and S.R. Hanna, 1986. Evaluation of Downwash Modification to the Industrial Source Complex Model. *Journal of the Air Pollution Control Association,* 36: 258–264.

Segal, H.M., 1983. Microcomputer Graphics in Atmospheric Dispersion Modeling. *Journal of the Air Pollution Control Association,* 23: 598–600.

Snyder, W.H., R.S. Thompson, R.E. Eskridge, R.E. Lawson, I.P. Castro, J.T. Lee, J.C.R. Hunt, and Y. Ogawa, 1985. The structure of the strongly stratified flow over hills: Dividing streamline concept. *Journal of Fluid Mechanics,* 152: 249–288.

Turner, D.B., 1969. Workbook of Atmospheric Dispersion Estimates. PHS Publication No. 999–26. U.S. Environmental Protection Agency, Research Triangle, Park, NC 27711.

Weil, J.C. and R.P. Brower, 1984. An Updated Gaussian Plume Model for Tall Stacks. *Journal of the Air Pollution Control Association,* 34: 818–827.

Weil, J.C., 1996. A new dispersion algorithm for stack sources in building wakes, Paper 6.6. Ninth Joint Conference on Applications of Air Pollution Meteorology with A&WMA, January 28–February 2, 1996. Atlanta, GA.

Weil, J.C., L.A. Corio, and R.P. Brower, 1997. A PDF dispersion model for buoyant plumes in the convective boundary layer. *Journal of Applied Meteorology,* 36: 982–1003.

Zhang, X., 1993. A computational analysis of the rise, dispersion, and deposition of buoyant plumes. Ph.D. Thesis, Massachusetts Institute of Technology, Cambridge, MA.

Zhang, X. and A.F. Ghoniem, 1993. A computational model for the rise and dispersion of wind-blown, buoyancy-driven plumes—I. Neutrally stratified atmosphere. *Atmospheric Environment,* 15: 2295–2311.

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Endnote 13

Fig. 6 in *Numerical study of the airflow over forest clearings,*
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Numerical study of the airflow over forest clearings

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Summary

In order to better understand the behaviour of the turbulent flow around forests interrupted by clearings, numerical simulations with a LVEL k-ε turbulence model have been performed. The effects of the clearing width on the flow field were studied for two-dimensional forest-clearing-forest sequences. Furthermore, three-dimensional calculations were conducted in order to investigate the influence of the clearing shape. The numerical results were validated against our own wind tunnel data. The impact of the clearing width on the flow field is marginal above and within the upstream forest area, but significant further downwind. With increasing clearing width, the volume flux through the downstream forest and the streamline patterns resemble more and more those of an individual forest stand. For the forest configuration with maximum investigated clearing width (a/H = 11, where H is the forest height), the flow around the forest downstream of the clearing is still clearly affected by the presence of the upstream forest area. With increasing clearing width, the mean bending moment coefficients of trees standing near the leeward clearing edges increase gradually. For small clearings, the influence of clearing shape (round or rectangular) on the flow field is marginal.

Introduction

In forest stands, clear-cut areas of different geometry can be found. They are induced by tracks, roads, intersections or they are created by forest fires or severe storms. Such clearings represent a discontinuity in the forest canopy causing the atmospheric flow to 'stumble' and to induce mean wind and turbulent perturbations. Thus, clearings can influence the wind stability of forest stands. However, there is still a lack of knowledge on the fluid mechanical behaviour.

The flow field around an individual forest stand can be subdivided schematically into seven distinct regions (see Belcher *et al.*, 2003): windward of the canopy the impact region, within the canopy the adjustment region and further downstream the canopy interior, above the canopy the canopy shear layer and above a roughness-change region, leeward of the canopy the exit region and the far wake. Many studies deal with the flow field near individual forest edges (e.g. Morse *et al.*, 2002 (wind tunnel and field); Li *et al.*, 1990; Liu *et al.*, 1996 (numerical studies); Raynor, 1971; Gash, 1986 (field studies)). Yang *et al.* (2006b) studied wind loadings on trees across a forest leading edge by employing a large-eddy simulation (LES) simulation. At the leading edge, the absolute values of both mean and extreme wind moments are high compared with those further downstream inside the forest stand. However, for $x/H > 8$, the wind moment is characterized by higher maximum-to-mean

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ratios, greater fluctuations relative to the local means, larger positive skewness and higher frequency of extreme values than in the edge region. According to this, trees inside the forest could be more vulnerable than established edge trees because wind damage is more likely associated with maximum wind moments rather than mean moments. At recently formed edges, the edge trees are likely more vulnerable than those inside the forest because they are exposed to unusually high wind loadings.

Bergen (1975, 1976) investigated in a field study the flow in a clearing of size 1 $H \times 5$ H. His smoke drift measurements showed that the recirculating vortices in clearings are highly intermittent. The flow states continuously alternate between recirculation and throughflow (see also Raupach *et al.*, 1987). Raupach *et al.* (1987) investigated the flow field in three clearings of different width (a/H = 4.3, 11.8 and 21.3) in a wind tunnel. Their results showed that the two roughness changes (rough-to-smooth and smooth-to-rough) accompanying the clearing have no significant upstream effects. The turbulence equilibrates very slowly downwind of the rough-to-smooth surface change, but quite rapidly downwind of the smooth-to-rough change. Just leeward of the clearing, an enhanced gust zone exists in which the peak gusts are much stronger than in an undisturbed canopy. For the smaller clearings, the flow patterns are apparently similar, though in the case a/H = 4.3 the main effects are somewhat attenuated (the results for the smaller clearings were unfortunately not published). Their experimental data of the wide clearing were used several times to validate numerical models, see Wilson and Flesch (1999) (k-l-model), Foudhil *et al.* (2005) (k-ε-model), Sogachev and Panferov (2006) (k-ω-model), Yang *et al.* (2006a) and Dupont and Brunet (2008) (LES models).

Miller *et al.* (1991a) simulated the airflow across an alpine, 3-H wide forest clearing by means of a steady-state, two-dimensional (2D) numerical model. The model results were compared with their own field data. Miller *et al.* (1991b) investigated the influence of the canopy density on the flow field in small clearings. For a canopy with dense understorey, two different clearing widths were investigated: 3 H and 5 H.

Stacey *et al.* (1994) investigated 2D clearings of varied width (a/H < 6.7) using an aeroelastic model of a 15-m high Sitka spruce stand. Their measurements of mean and extreme bending moments (BMs) at selected individual trees showed that trees standing close to the sheltered upwind side of a clearing experience the same extreme BMs as trees amid vast forests. At the exposed downstream side of a clearing, the extreme BMs are high; however, the moments decrease rapidly within the first few rows. As soon as even the smallest clearing exists within the forest, the extreme BMs increase sharply. A one-tree height wide clearing virtually doubles the extreme moment on the exposed forest edge (compared with the mid-forest value). Trees of the second to 10th row experience lower extreme BMs than mid-forest trees.

Flesch and Wilson (1999) carried out field measurements in two forest cutblocks of different width (a/H = 1.7 and 6.1), in which immature trees had remained. Both cutblocks were part of shelterwood systems consisting of a series of identical cutblocks separated by unharvested forest strips. They observed that the most effective wind shelter in clearings occurs within three tree heights of the upwind forest trailing edge. In this 'quiet zone', the average wind velocity and the turbulence are reduced relative to their reference levels in a larger clearing.

Sanz Rodrigo *et al.* (2007) investigated in a wind tunnel study the influence of the forest porosity and the length of the leading forest (L = 2, 5 and 10 H) on the flow field within 2D clearings (a/H = 5). Additionally, the flow field leeward of varied porous shelterbelts (L = 2 H) was studied. The results of their particle image velocimetry measurements showed that the porosity has a significant impact in the short upwind forest and shelterbelt cases. However, in the long upwind forest cases, where there is hardly any air entrainment from the upstream forest, the porosity effect is considerably attenuated.

The impact of canopy morphology (more precisely the plant density and vertical distribution of the leaf area density) on the spatial variation of the flow characteristics particularly in the adjustment region of a forest area located downwind of a 21.2-H wide clearing was studied by Dupont and Brunet (2008). With increasing canopy density, the flow adjusts faster and turbulent features become more marked. The length of the adjustment region increases significantly, when the forest is characterized by a sparse trunk space, because then a sub-canopy wind jet from the leading edge is formed. The position and magnitude of the enhanced gust zone are related to the mean upward motion formed behind the windward edge around canopy top.

There are key parameters such as the shear length *Ls* or the tallest tree height which can be used to generalize results so that they can be applied in other forest conditions (tree height, forest structure etc.), see Finnigan (2000), Gardiner *et al.* (2005).

K-ε-models were used several times in order to study the flow around forests. Usually the standard model, see e.g. Launder and Spalding (1974), was modified by inserting additional source and sink terms in the transport equations for momentum and for the turbulent quantities (turbulent kinetic energy (TKE) k and turbulent dissipation rate (TDR) ε). Table 1 gives an overview of these terms taking into account the momentum absorption, the development of wake turbulence as well as the enhancement of the kinetic energy dissipation by a 'spectral shortcut' (Finnigan, 2000). The constants used in former models are summarized in Table 2.

In the perspective of better assessing windthrow risks of forest areas interrupted by clearings, a better understanding of the flow behaviour is essential. Latest research results indicate that the gust velocity or the gust momentum is not the only quantity on which load assessments should be based. It seems that the ratio of gust velocity to mean velocity plays an important role. In other words, it makes a difference whether a gust of a constant velocity is acting on a forest edge associated by strong or weak mean flow. A porous body in a mean flow field will always lead to an effective aerodynamic shape of the body, which usually does not coincide with the physical shape. This effect was not accounted for in the past. In order to investigate this effect, first of all, the mean flow field must be determined for standard edge configurations. Therefore, a numerical study was performed in which 2D clearings of different width as well as three-dimensional (3D) clearings of different shape have been investigated. For the study, a software package based on the LVEL k-ε turbulence model was used (FLOVENT/Flomerics Ltd). The forest stands were simulated by highly porous and homogenous bodies characterized by flow resistances (via pressure loss coefficients) and a simplified sink term for the TKE. The CFD-Code FLOVENT was used in former studies dealing with wind shelter in the intermediate field of double-arranged mound-mounted shelterbelts (see Frank, 2005).

Table 1: Additional source and sink terms usually used to model plant canopies (vegetation parameters: c_d = drag coefficient, a = leaf area density; c_{pkw}, c_{dkw}, $c_{p\varepsilon w}$, $c_{d\varepsilon w}$ = constants; grid-dependent flow variables: $|U| = \sqrt{U_i U_i}$ = absolute velocity, k = TKE, ε = TDR)

	Source term	Sink term
Equations of momentum		$-c_d a \lvert U \rvert U_j$
Equation of the TKE	$c_{pkw} c_d a \lvert U \rvert^3$	$-c_{dkw} c_d a \lvert U \rvert k$
Equation of the TDR	$c_{p\varepsilon w} \frac{\varepsilon}{k} c_d a \lvert U \rvert^3$	$-c_{d\varepsilon w} c_d a \lvert U \rvert \varepsilon$

Methods

CFD-Code FLOVENT

The used CFD-Code offers a LVEL k-ε turbulence model to close the Reynolds-averaged Navier–Stokes equations, see Flomerics Limited (2005). The turbulent viscosity ν_t is determined in near-wall regions by a blending of the turbulent viscosity $\nu_{t,\,k\text{-}\varepsilon}$, calculated by the classical k-ε approach, and the turbulent viscosity $\nu_{t,\,LVEL}$, calculated by an algebraic LVEL approach using a characteristic length (L) and velocity (VEL) scale. In addition, wall functions for the treatment of wall-adjacent cells are included. The governing equations are solved on a structured, staggered grid, using the finite volume method. Underlying discretization schemes are first-order upwind and second-order central differences for the convection and the diffusion terms, respectively.

The numerical wind tunnel

The first step in numerical modelling was to build a numerical wind tunnel with boundary conditions and an undisturbed atmospheric boundary layer flow similar to that of the wind tunnel experiments of Frank and Ruck (2007), see below.

Table 2: Constants used in different k-ε models

	σ_k	σ_ε	c_μ	$c_{\varepsilon 1}$	$c_{\varepsilon 2}$	c_{pkw}	c_{dkw}	$c_{p\varepsilon w}$	$c_{d\varepsilon w}$
Foudhil (2002) (after Krzikalla (2005))	1	1.3	0.09	1.44	1.92	1	4.0	1.5	4.3
Foudhil *et al.* (2005)	0.74	1.3	0.026	1.13	1.90	0.8	4.0	1.5	3.24
Green (1992)	1	1.3	0.09	1.44	1.92	1	4.0	1.5	6
Katul *et al.* (2004)	1	1.88	0.03	1.44	1.92	1	5.1	1.5	2.4
Krzikalla (2005)	1	1.3	0.09	1.44	1.92	0	4.0	0	4.3
Launder and Spalding (1974)	1	1.3	0.09	1.44	1.92	Standard model			

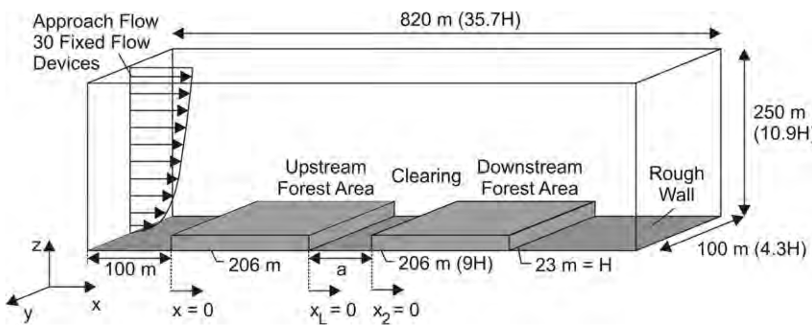


Figure 1. Sketch of the numerical wind tunnel.

A sketch of the numerical wind tunnel is given in Figure 1. The ground level was modelled as a rough wall with an estimated equivalent sand grain roughness. The boundary faces of the solution domain are defined as open in x-direction and as symmetric in the other two directions (open = a free boundary of constant pressure through which air can flow, symmetrical = a frictionless, impermeable and adiabatic planar surface through which neither air nor heat can flow). The atmospheric approach flow was determined at the beginning of the solution domain by means of 30 fixed flow devices. Values of the mean horizontal velocity u, of the TKE and the TDR were defined for each fixed flow device.

The forest areas were modelled as volume resistances via an estimated pressure loss coefficient $k_r = \Delta p/(0.5\rho \cdot u^2) = 0.8\ m^{-1}$. Its vertical distribution with height was simplified and assumed as homogenous. Since it is not possible in FLOVENT to define terms corresponding to those in Table 1 depending on two or more grid-dependent flow variables, simplified sink terms for the TKE were defined at the forest edges by inserting collapsed linear sources of the form $S\varphi = C\varphi \cdot (V\varphi - \varphi)$, with $C\varphi = 0.6$, $V\varphi = 0.0$ and φ = TKE.

Both 2D and 3D computations were performed. 2D means the forest areas as well as the clearing are infinitely long in y-direction and all variables remain constant in this direction throughout the domain. In case of the 3D computations, the flow quantities are variable also in y-direction. Forest configurations with 2D clearings of varied width were investigated numerically, whereas the width (i.e. the along-wind length of the clearing, see Figure 1) ranged from 1 to 11 times the forest height. Additionally, an individual forest without clearing was tested being as long as the upstream forest areas of the clearing configurations (L = 206 m = 9 H, below also referred to as 'short forest'). Furthermore, two 3D configurations with clearings of different shape were studied, namely a rectangular clearing of size 1 H × 1 H and an (approximately) round clearing with a diameter of 1 H.

The maximum grid size of the 2D calculations in streamwise and vertical direction amounts to 2.5 m. In the lower part of the solution domain

($z \leq 100$ m), the grid was refined to a maximum grid size of 1.25 m. The total number of grid cells amounted to 73 239 (system grid: 331 × 1 × 108 = 35 748 grid cells, refined region: 659 × 1 × 81 = 53 379 grid cells). In comparison to the 2D calculations, the maximum grid size of the 3D calculations was doubled (5 and 2.5 m, respectively). The total number of grid cells amounted to 598 884 in the rectangular clearing configuration and 736 209 in the round clearing configuration.

From the computed horizontal velocities u, wind loadings on trees were estimated. For this purpose, BM coefficients were calculated for trees standing at the downwind edges of the 2D clearings of different width as well as within the forest areas at different distances from the leading forest edges. The BM is calculated by applying the following function:

$$\mathrm{BM} = \int_0^H 0.5 \cdot \rho \cdot u(z) \cdot |u(z)| \cdot c_d \cdot \mathrm{a} \cdot A(z) \cdot \mathrm{z}dz,$$

where ρ is the air density, c_d the drag coefficient, a the plant area density and $A(z)$ the base area of a tree. The dimensionless BM coefficient BMCoeff is defined as

$$\mathrm{BMCoeff} = \frac{\mathrm{BM}}{0.5 \cdot \rho \cdot u_{\mathrm{ref}}^2 \cdot H^3},$$

where u_{ref} is the horizontal velocity of the undisturbed approach flow ($x = -4.3\ H$) in a reference height $z_{\mathrm{ref}} = 1.9\ H$. The calculations based on the following assumptions: (1) $c_d \cdot a = k_r = 0.8\ \mathrm{m}^{-1}$, (2) vertically constant leaf area density and (3) the base area of a tree is $1.73 \times 1.73\ \mathrm{m}^2 = 3.0\ \mathrm{m}^2$ (corresponding to a stand density of 3340 $\mathrm{trees \cdot ha}^{-2}$). The length and width of the single trees are identical to the tree spacing in the investigations of Stacey *et al.* (1994) and Gardiner *et al.* (1997) (pattern K1) so that a comparison with their wind tunnel results is facilitated.

Validation

The numerical data were validated against the wind tunnel data described in detail in Frank and Ruck (2007). The experimental investigations were performed in the atmospheric boundary layer wind tunnel of the Laboratory of Building and Environmental Aerodynamics, Institute for Hydromechanics, University of Karlsruhe. The model forest consists of 6700 individual standard conifer trees of height $H = 11.5 \pm 0.5$ cm (with the used model scale of 1:200, this corresponds to 23 ± 1 m in nature). A side-view photo of the model forest is given in Figure 2. The rigid standard tree is composed of a conical, porous crown (averaged height $K = 0.52 \cdot H$, diameter $\approx 0.22\ H$) and a cylindrical trunk (averaged height $S = 0.48\ H$, diameter = $0.03\ H$). The mean drag coefficient c_d of the standard tree amounts to 1.18 and lies in the range of natural $c_{d,\mathrm{dyn}}$ values of conifer trees (see Rudnicki *et al.*, 2004), $c_{d,\mathrm{dyn}} = 0.5 \cdot \rho \cdot u^2 \cdot A(u)$, where ρ is the air density, u the approach velocity and $A(u)$ the velocity-dependent front area). The distance between the trees amounts to $0.18\ H$ (4.1 m) in streamwise direction and $0.17\ H$ (4.0 m) in lateral direction. With this forest configuration, a stand density of 2400 trees m^{-2} in the model and 600 trees m^{-2} in nature was realized. The model forest possesses a structured and closed canopy. It extends over the entire wind tunnel width so that lateral flows are suppressed and the flow field is quasi 2D. The model forest was divided by the clearing into two separated forest areas of equal length $L = 9\ H$.

Two forest configurations with clearings of the width $a/H = 1$ and 5 were investigated to date. The velocity measurements were performed by means of a 2D laser Doppler anemometry system. At each measuring point, ~26 600 data points were collected with a sampling

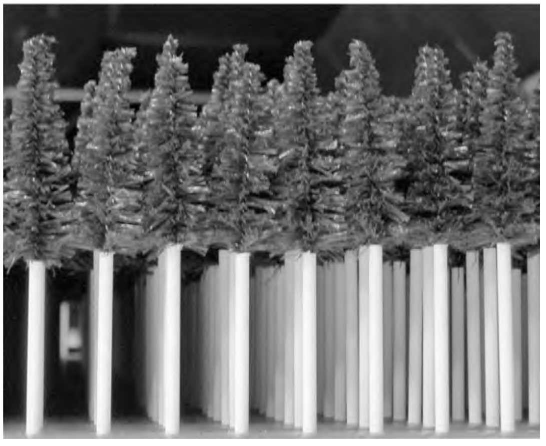


Figure 2. Photo of the model forest.

frequency of 500 Hz. The TKE was calculated from the measured standard deviations of the streamwise and the vertical velocities, u' and w', according to TKE = $0.75\cdot(u'(x, z)^2 + w'(x, z)^2)$. This relationship results from the conventional equation of the TKE = $0.5\cdot(u'(x, z)^2 + v'(x, z)^2 + w'(x, z)^2)$, see Stull (1988), assuming that $v'^2 = 0.5\cdot(u'^2 + w'^2)$.

Figure 3 shows computed and measured vertical profiles of horizontal velocity $u(z)$ and TKE(z) at different streamwise positions in the empty numerical and physical wind tunnels. In the empty physical wind tunnel, the horizontal velocity increases slightly and the TKE decreases somewhat in streamwise direction over a distance of $\Delta x = 16.2\ H$ for $0.5 < z/H < 3.5$. Averaged values of the flow quantities were calculated from the experimental data as target values for the undisturbed atmospheric boundary layer flow in the numerical wind tunnel. The agreement between numerical data and averaged experimental data is quite satisfactory at the origin of the Cartesian co-ordinate system ($x = 0$ in Figure 1). Furthermore, it can be seen that the computed mean flow is in an equilibrium state whereas the computed TKE varies slightly in flow direction.

For a first validation, the configuration with the 1-H wide clearing was selected. Computed and measured vertical profiles of the streamwise velocity u and the TKE are plotted in Figures 4 and 5, respectively. The agreement of the velocity profiles is all in all quite satisfactory. The TKE profiles show partially differences: the computed TKE is overestimated particularly close to the upper forest edge in the vicinity of the leading edge and slightly in the upper part of the solution domain ($z/H > 2$). The latter is probably the consequence of the fact that the TKE does not completely equilibrate, as was shown in Figure 3. However, the agreement is quite good at lower heights in the region of the clearing.

Results and discussion

2D clearings of varied width

Streamlines

In Figure 6, streamlines of three forest configurations with varied clearing width are shown: a/H = 1, 5 and 9. In all investigated configurations, recirculation zones occur in the lee of both forest areas (upstream and downstream of the clearing). Furthermore, recirculation zones can be observed inside the forests themselves, whereas those inside the downstream forest areas solely exist with wide clearings. In the smallest clearing (a/H = 1), the recirculation zone extends over the entire clearing width. In the wider clearings, the length of the recirculation area amounts to ~2.8 H and remains quite constant.

The presence of the forest canopy induces a pressure gradient, which starts to decelerate the undisturbed approach flow slightly upstream

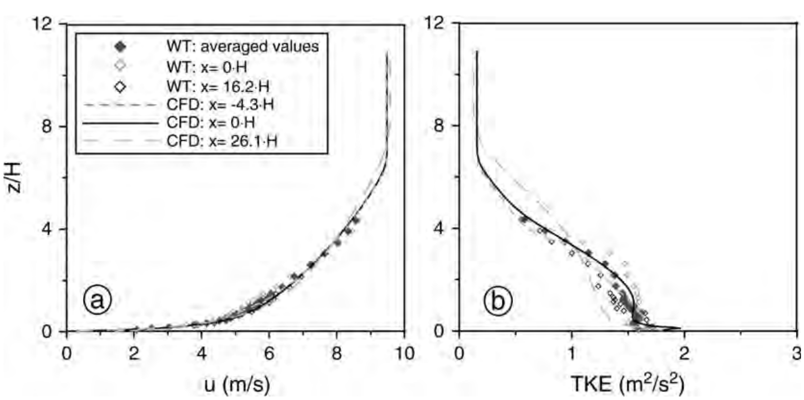


Figure 3. The undisturbed atmospheric boundary layer flow: comparison of measured (symbols) and computed (lines) vertical profiles of (a) the streamwise velocity u and (b) the TKE.

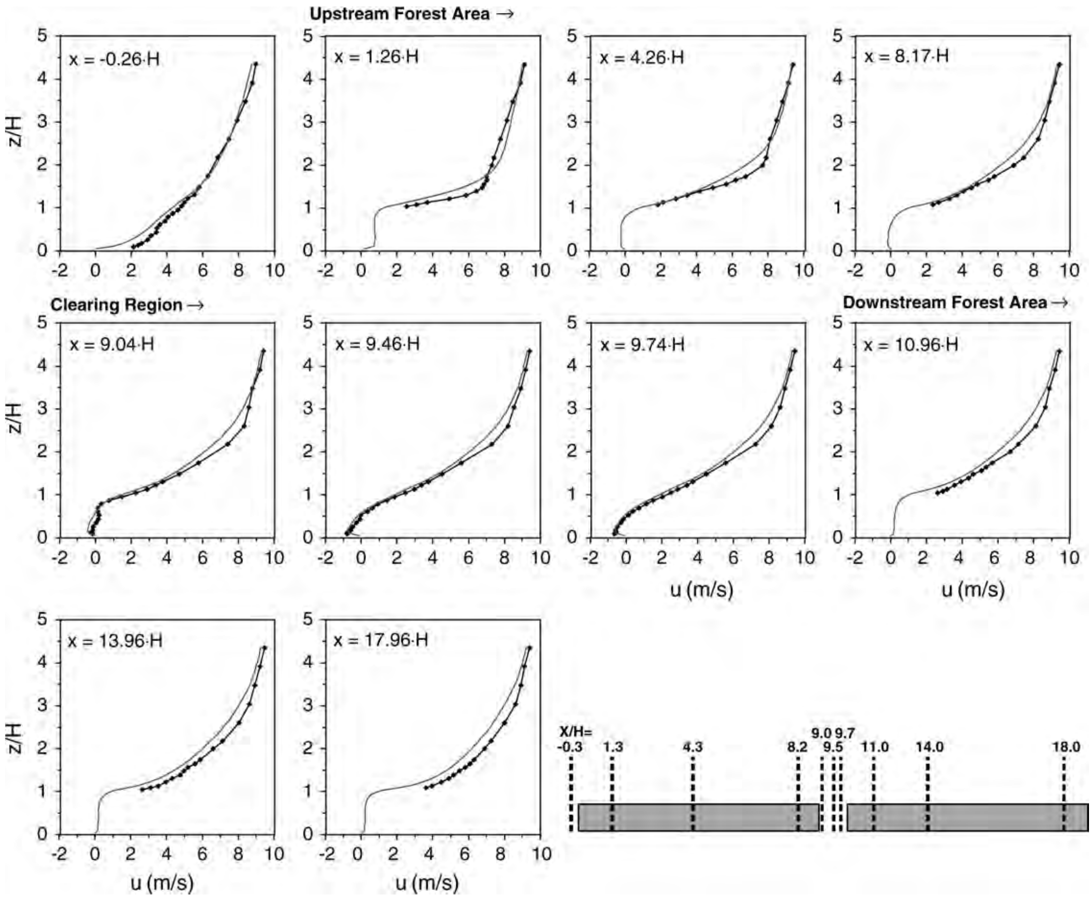


Figure 4. Comparison of measured (symbols) and computed (lines) vertical profiles of the streamwise velocity *u*. Forest with clearing of width a/H = 1.

from the leading forest edge. The airflow penetrates to some extent through the windward edge into the stand, where it is decelerated further on and, due to momentum conservation, deflected upward, passing through the canopy top in the windward half of the upstream forest area. Close to the trailing edge of the upstream forest area, the flow above the canopy is deflected slightly downward and passes partly into the forest area.

The flow behaviour around and through the downwind forest area depends strongly on the clearing width. If the clearing is very small (a/H = 1), the region between the two forest areas is dominated by the recirculation zone. In this case, the impact of the clearing on the flow above top height is quite slight. The slight downward motion of the flow continues over the clearing and even over the downwind forest area. The air penetrates into the downwind forest area through the upper part of the leading edge and the front part of the canopy top. No recirculation zone occurs inside this forest area.

With augmenting clearing width, the penetration of air into the clearing region (z/H < 1) increases and, as a consequence, the inflow through the leading edge of the downstream forest area as well as the outflow through the canopy top are also augmented. In these cases, the inflow takes place over the total forest height. With increasing clearing width, the flow behaviour around and through the downwind forest area resembles more and more that of the upwind forest area.

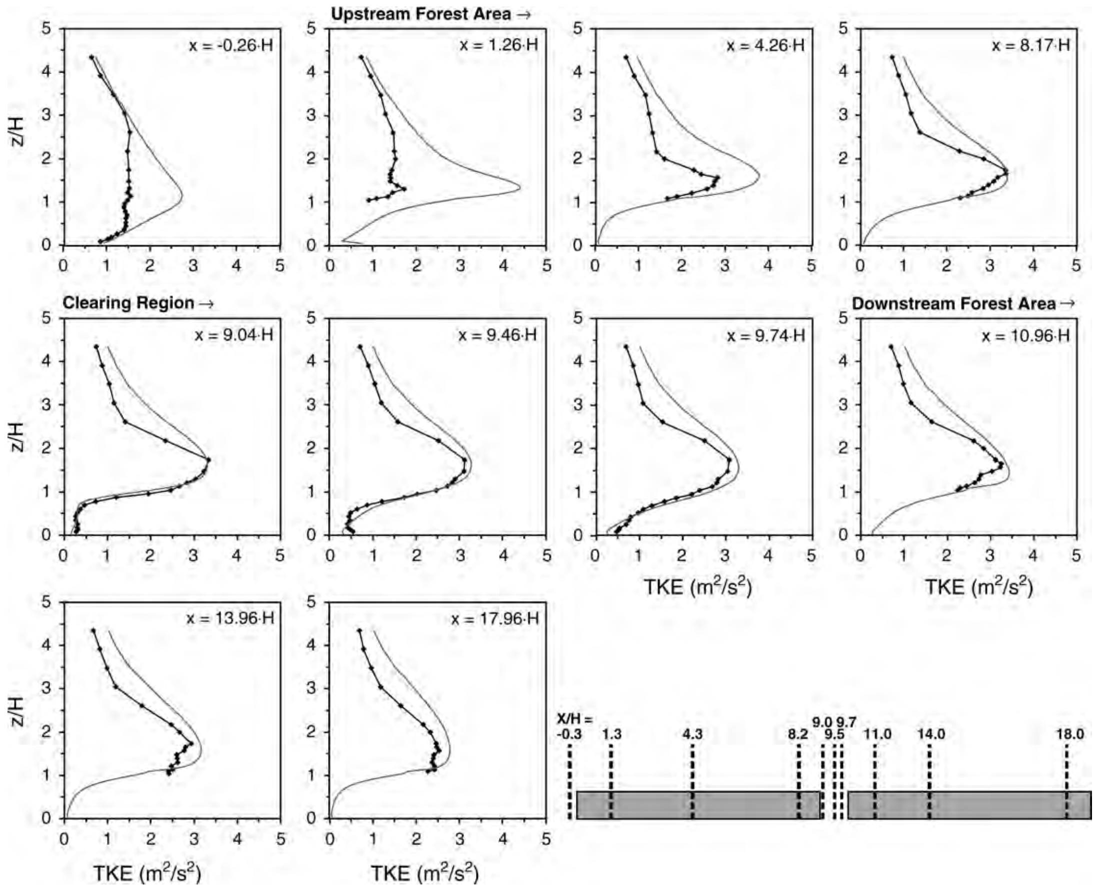


Figure 5. Comparison of measured (symbols) and computed (lines) vertical profiles of the TKE. Forest with clearing of width *a*/*H* = 1.

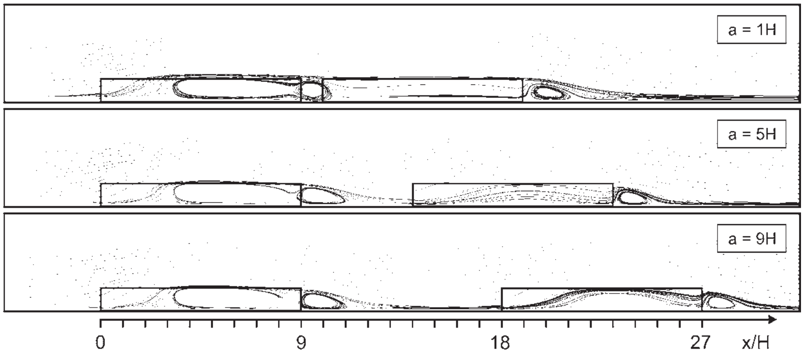


Figure 6. Streamlines of three forest configurations with clearings of width *a*/*H* = 1 (top), *a*/*H* = 5 (middle) and *a*/*H* = 9 (bottom).

Recirculation zones in forest clearings were observed also by Bergen (1975), Raupach *et al.* (1987), Miller *et al.* (1991a, b), Stacey *et al.* (1994) and Sanz Rodrigo *et al.* (2007). Bergen (1975) and Raupach *et al.* (1987) showed that such recirculating vortices are highly intermittent. A large recirculation zone (5 *H* wide and 0.7 *H* high) within a dense forest ($c_d ah$ = 2.04) was also observed in the numerical simulation of Krzikalla (2005). The centre of this recirculation zone was located 11 *H* downstream from the leading forest edge. Our results show that in wide clearings, the reattachment length is not influenced by the clearing width. Such behaviour was also observed in the intermediate field of double-arranged windbreak systems (see Frank, 2005; Frank and Ruck, 2005).

Volume flow rates

In Table 3, the volume flow rates through the edges of both forest areas are summarized. Absolute values as well as percentage values being related to the sum of the respective volume inflows are given for all investigated forest configurations. The width of the clearing affects particularly the volume flow rates of the downwind forest area and only slightly those of the upwind one. With increasing clearing width from a/H = 1 up to 11, the total volume inflows increase by 2 and 355 per cent, respectively. For the widest investigated clearing (a/H = 11), the total volume inflow of the upstream forest area amounts to 99.5 per cent of the value of the single forest configuration. The corresponding value of the downstream forest area amounts to only 72 per cent, indicating that the influence of the upstream forest area still exists.

Contour plots and horizontal profiles

In Figure 7, contour plots of the streamwise velocity component *u* are shown for three forest configurations: small forest without clearing (top) and forests with clearings of the width a/H = 1 (middle) and a/H = 9 (bottom). Corresponding contour plots of the vertical velocity component *w* and the TKE are given in Figures 9 and 11, respectively. Horizontal profiles of the streamwise velocity *u* are depicted in Figure 8 for configurations with varied clearing width. Figure 8a–c shows profiles close to the upper forest edge (z/H = 1.13) along the whole stand and Figure 8d–f shows three additional profiles at different heights (z/H = 1.5, 0.5 and 0.25) in the region of the clearing. Besides the computed values, also measured values for two configurations with a/H = 1 and 5 are given. Corresponding profiles of the vertical velocity *w* and the TKE are shown in Figures 10 and 12 respectively.

As can be seen in all these figures, the clearing width has no significant influence on the flow field upstream of the clearing. Similar observations were also made by Raupach *et al.* (1987).

In the near wake of the short forest, the horizontal and the vertical velocities decrease slightly near the ground ($z/H \leq 0.52$) due to the formation of the recirculation zone (Figures 8e,f and 10e,f). Further downstream, the horizontal and the vertical velocities increase with increasing distance to the forest edge. By contrast, the TKE increases quickly in the near wake and decreases gradually further downstream (Figure 12e,f). Gash (1986) observed in his field study downwind of a forest–heath interface ($x/H > 5$ at a height z/H = 0.35) also an increase of the horizontal velocity and a slight decrease of the vertical and horizontal standard deviations (indicating that also TKE decreases).

In comparison to the horizontal profiles in the wake of a short forest, the profiles in the clearing region are in general more curved (see Figures 8, 10 and 12). The differences between the profiles are very small in the windward clearing halves and increase further downstream, particularly near the leeward edges of the clearings in the impact regions of the downstream forest areas. Both the numerical and the experimental results show that in the clearing region – when compared with the values of the short forest configuration – (1) the horizontal velocities decrease in all four illustrated heights (Figure 8b,d–f), (2) the vertical velocities increase for $z/H \geq 1.13$ (Figure 10b,d) and are similar at ground level (Figure 10e,f) and (3) the TKE decreases for $z/H \leq 0.52$ (Figure 12e,f). Near the ground, the reduction of the horizontal velocities as well as the TKE is highest near the leeward clearing edges due to the shelter effects of the downstream forest areas. For $z/H \geq 1.13$ and $a/H \geq 3$, the computed TKE values show a strong, unrealistic increase close to the leading edges of the upstream forest areas (Figure 12b,d); this increase is not verified by the experimental results, but it was acceptable in the view of the

Table 3: Volume flow rates for forest configurations with clearings of varying width *a*/*H*

Clearing width		Upstream forest area					Downstream forest area				
		Outflow		Inflow		NetVF*	Outflow		Inflow		NetVF*
a/*H*	Forest edge	m^3/s	%	m^3/s	%	m^3/s	m^3/s	%	m^3/s	%	m^3/s
1	Windward	0	0	5269	88	5269	246	20	869	70	624
	Leeward	521	9	253	4	−267	824	66	0	0	−824
	Upper	5452	91	450	8	−5002	172	14	373	30	201
	Σ			5972					1242		
3	Windward	0	0	5270	88	5270	0	0	1924	87	1924
	Leeward	558	9	197	3	−361	879	40	0	0	−879
	Upper	5446	91	537	9	−4909	1325	60	280	13	−1045
	Σ			6003					2204		
5	Windward	0	0	5273	87	5273	0	0	2780	89	2780
	Leeward	604	10	143	2	−461	917	29	0	0	−917
	Upper	5435	90	622	10	−4813	2212	71	350	11	−1862
	Σ			6038					3130		
7	Windward	0	0	5276	87	5276	0	0	3317	88	3317
	Leeward	642	11	97	2	−545	931	25	0	0	−931
	Upper	5424	89	693	11	−4731	2819	75	433	12	−2385
	Σ			6066					3750		
9	Windward	0	0	5278	87	5278	0	0	3674	88	3674
	Leeward	671	11	63	1	−608	914	22	0	0	−914
	Upper	5415	89	744	12	−4671	3268	78	509	12	−2759
	Σ			6086					4182		
11	Windward	0	0	5280	87	5280	0	0	3912	89	3912
	Leeward	691	11	40	1	−650	794	18	0	0	−794
	Upper	5409	89	779	13	−4630	3619	82	502	11	−3117
	Σ			6099					4414		
Single forest	Windward	0	0	5284	86	5284					
	Leeward	730	12	5	0	−724					
	Upper	5399	88	840	14	−4560					
	Σ			6128							

* Negative values, outflow; positive values, inflow.

differences observed in the vicinity of the leeward stand edge (Figure 5).

Reference values of the horizontal velocity u_{ref} and the TKE_{ref} in the undisturbed atmospheric boundary layer flow are also given in Figures 8b,d–f and 12b,d–f, respectively. The horizontal velocities in the clearings are all smaller than the corresponding height-dependent reference velocities, indicating that the aerodynamic wind forces in the clearings are reduced in comparison to those in the open field. For example, for the widest investigated clearing (a/H = 11), the maximum of u/u_{ref} amounts to solely 0.56 at a height z/H = 0.52. Thus, at this location, the mean wind force amounts to only 27 per cent of the wind force in the open field. However, apart from the lower part of the near wake, the TKE values are increased in the whole region of the clearing when compared with the reference values. At a height z/H = 0.52, the maximum of TKE/TKE_{ref} amounts to 2.1; at forest height, the factor is even higher. This suggests that, in contrast to the mean wind forces, the turbulent wind forces increase.

Above the downstream forest area at a height z/H = 1.13, an increase of the clearing width results in an augmentation of the mean streamwise and vertical velocities close to the leading edge (Figures 8c and 10c). Furthermore, the numerical results show that a broadening of the clearing

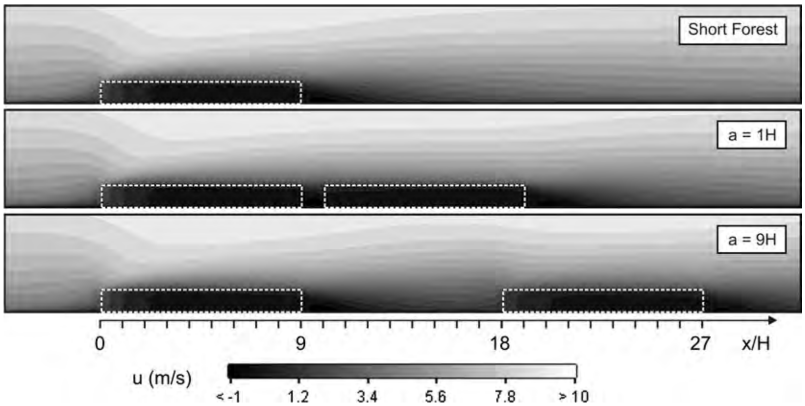


Figure 7. Contour plots of the streamwise velocity component *u* in m/s for three forest configurations: forest without clearing (top) and forests with clearings of the width *a*/*H* = 1 (middle) and *a*/*H* = 9 (bottom).

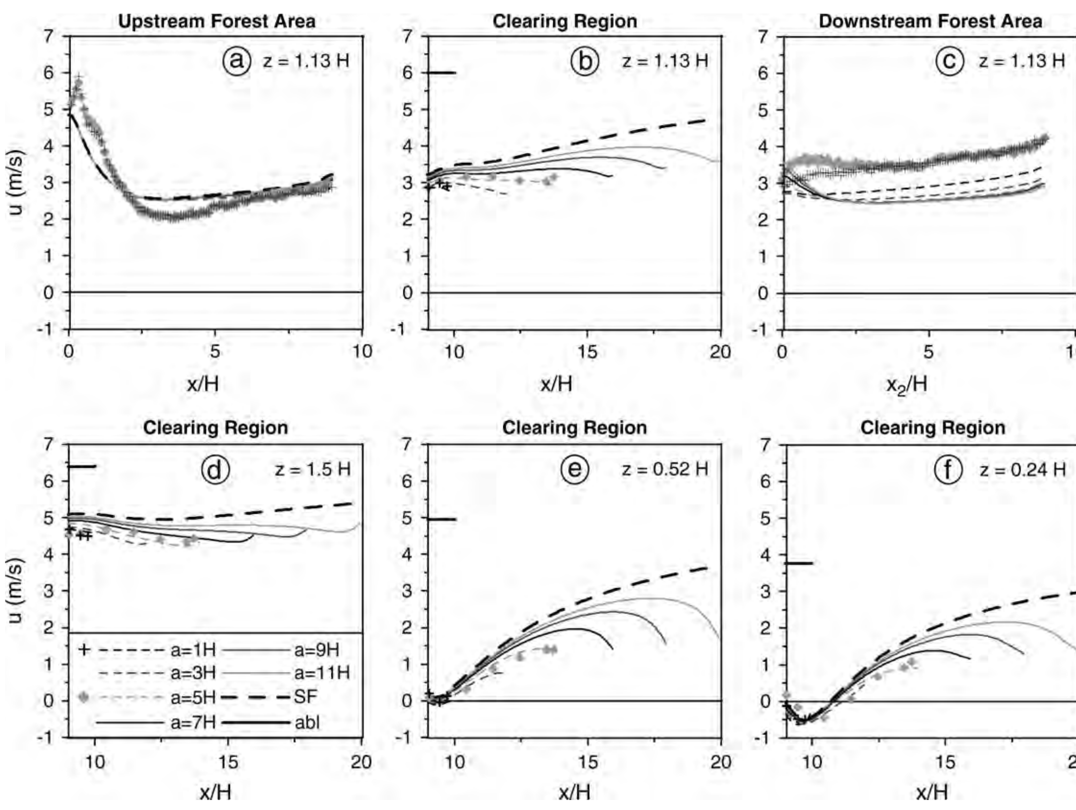


Figure 8. Horizontal profiles of the streamwise velocity component *u* for forest configurations with clearings of varying width *a*/*H* at a height *z*/*H* = 1.13: (a) above the upstream forest area, (b) in the clearing region and (c) above the downstream forest area. Further profiles in the clearing region: (d) at *z*/*H* = 1.5, (e) at *z*/*H* = 0.52 and (f) at *z*/*H* = 0.24 (symbols, experimental results; lines, numerical results; SF, short forest; ABL, reference value of the undisturbed atmospheric boundary layer flow).

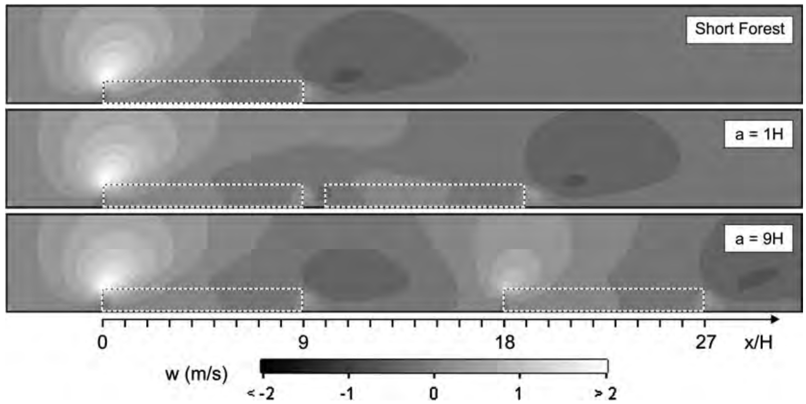


Figure 9. Contour plots of the vertical velocity component w in m/s for three forest configurations: forest without clearing (top) and forests with clearings of width a/H = 1 (middle) and a/H = 9 (bottom).

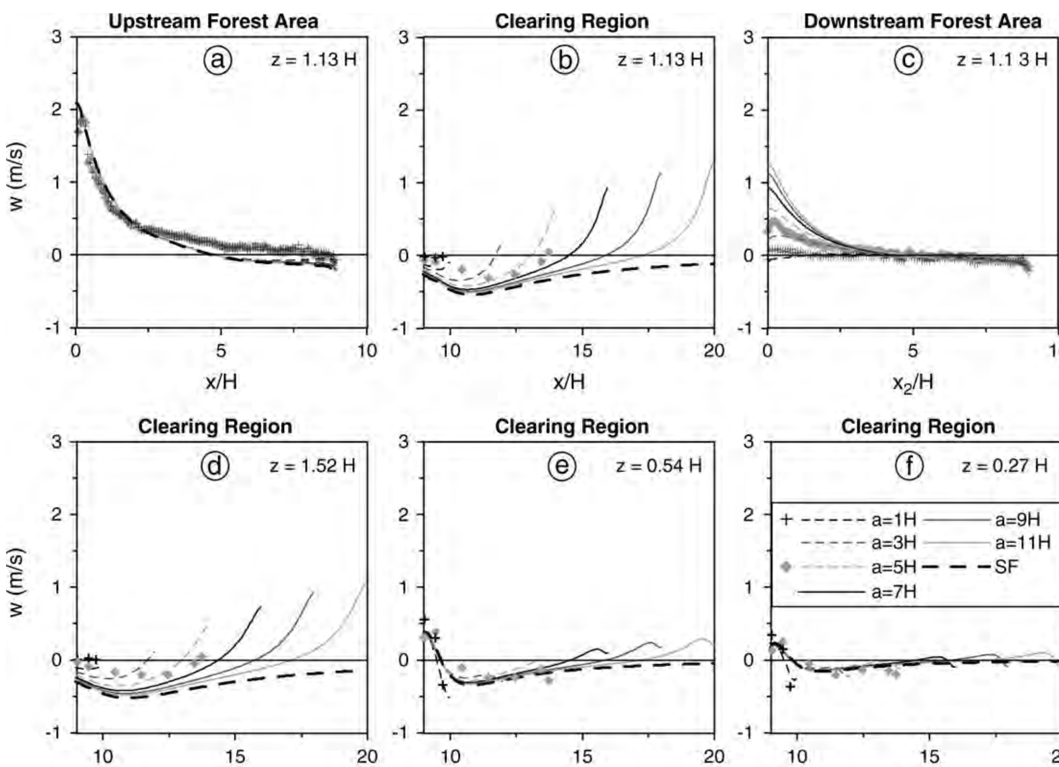


Figure 10. Horizontal profiles of the vertical velocity component w for forest configurations with clearings of varying width a/H at a height z/H = 1.13: (a) above the upstream forest area, (b) in the clearing region and (c) above the downstream forest area. Further profiles in the clearing region: (d) at z/H = 1.52, (e) at z/H = 0.54 and (f) at z/H = 0.27 (symbols, experimental results; lines, numerical results; SF, short forest).

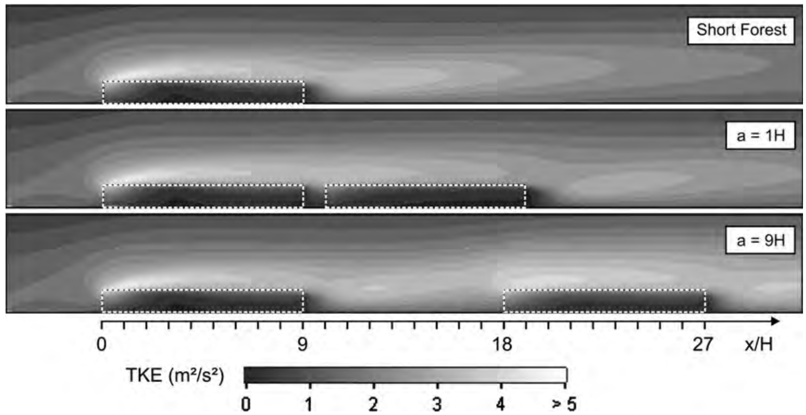


Figure 11. Contour plots of the TKE in m^2/s^2 for three forest configurations: Forest without clearing (top) and forests with clearings of width *a*/*H* = 1 (middle) and *a*/*H* = 9 (bottom).

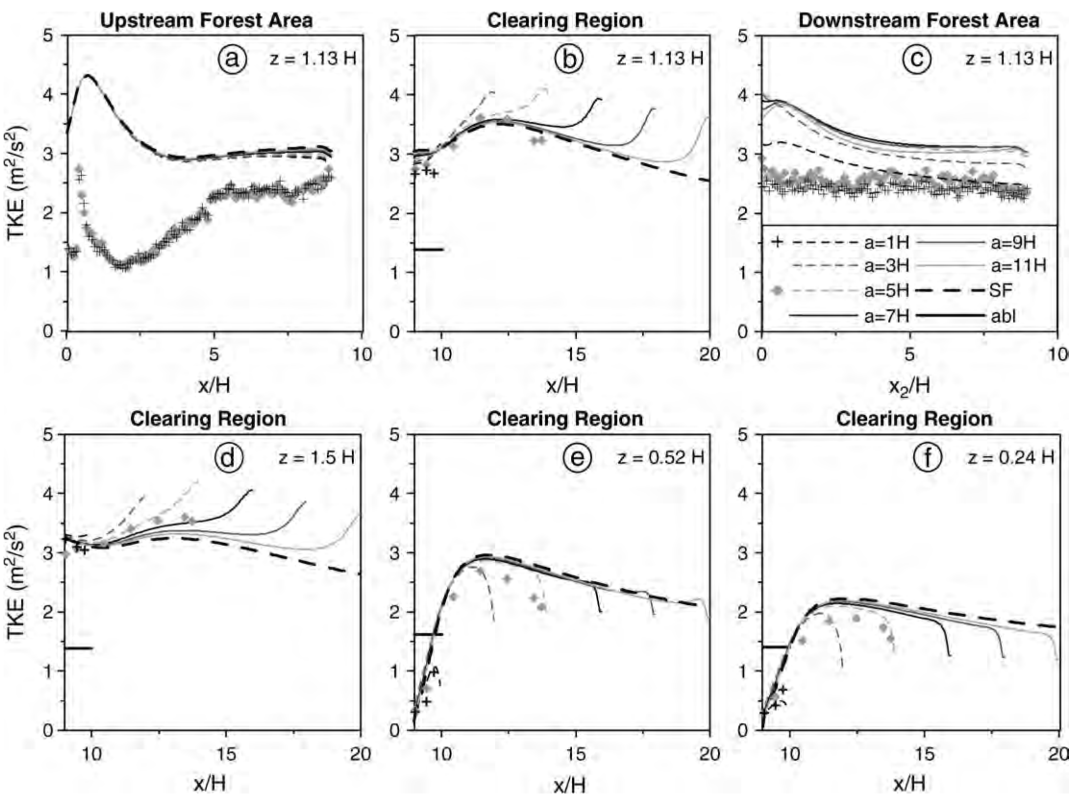


Figure 12. Horizontal profiles of the TKE for forest configurations with clearings of varying width *a*/*H* at a height *z*/*H* = 1.13: (a) above the upstream forest area, (b) in the clearing region and (c) above the downstream forest area. Further profiles in the clearing region: (d) at *z*/*H* = 1.5, (e) at *z*/*H* = 0.52 and (f) at *z*/*H* = 0.24 (symbols, experimental results; lines, numerical results; SF, short forest; ABL, reference value of the undisturbed atmospheric boundary layer flow).

from $a/H = 1$ up to 3 induces a strong increase of the TKE along the whole downstream forest area (Figure 12c). This strong increase is not verified by the experimental results (and is most likely a consequence of the unrealistic high TKE values in the region of the clearing observed for configurations with $a/H \geq 3$). Likely due to the overestimated TKE values, the horizontal velocities are somewhat underestimated for $a/H \geq 3$ (Figure 8c). For wider clearings, the TKE increases slightly for $3 \leq a/H \leq 7$, but decreases slightly for $a/H > 7$.

The general flow behaviour in the clearing resembles strongly that in the intermediate field of double-arranged windbreak systems of variable width (Blenk and Trienes, 1956; Frank, 2005). Despite differences in upwind conditions, the field data of Flesch and Wilson (1999) also show a relative good agreement for the two investigated clearings of different width ($a/H = 1.7$ and 6.1) when the wind statistics are plotted together vs x/H. By contrast, Miller *et al.* (1991b) observed in their numerical study that due to a reduction of the clearing width from $a/H = 5$ to 3, the general wind velocities in the clearing are reduced by about eightfold and the vorticity is greatly increased. This finding is very astonishing; especially the velocity seems to be reduced significantly not only inside the clearing but also above the adjacent forest areas up to a height of $z/H = 3$. The experimental data of Raupach *et al.* (1987) – plotted by Flesch and Wilson (1999) in their Figure 9 – show that in a short clearing ($a/H = 4.3$), the mean horizontal velocity as well as the TKE are reduced near the windward clearing edge at a height $z/H = 0.4$ when compared with a large clearing ($a/H = 21.3$). Further upstream in the clearing, the differences in the wind statistics are, however, small. These observations agree well with ours.

Estimate of wind loadings on trees

In Figure 13, mean BM coefficients BMCoeff for trees standing at the downwind edges of clearings are shown as a function of the clearing width. The mean BM coefficients increase with increasing clearing width. In comparison to the BMCoeff of the short forest, the BMCoeff of the configuration with the widest investigated clearing ($a/H = 11$) is still small, indicating that trees standing at the leeward edge of this clearing are

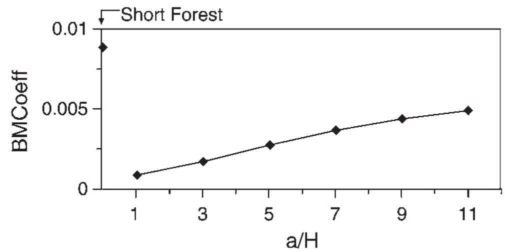


Figure 13. Mean BM coefficients as a function of the clearing width a/H.

still sheltered by the presence of the upstream forest area. The relationship between BMCoeff and a/H is nearly linear. The agreement between our results and the experimental data of Stacey *et al.* (1994) and Gardiner *et al.* (1997) is quite good. Their data confirm our calculations and the magnitude of their coefficients is surprisingly similar to ours in view of the quite different forest models and the different approach flow characteristics.

Mean BM coefficients are plotted in Figure 14 over the downstream distance from the leading forest edges for the short forest and for two forest configurations with clearing (a/H = 1 and 11). In the two latter cases, the leading edges are those of the downstream forest areas. The differences between the curves are highest immediately at the leading edge and decrease rapidly with increasing distance to the edge. The maximum BM coefficient of the short forest ($BMCoeff_{max} = 0.0088$) is around 10 times higher than that of the forest with the small clearing ($BMCoeff_{max} = 0.0009$) and ~1.8 times higher than that of the forest with the wide clearing ($BMCoeff_{max} = 0.0049$). In a distance of two times the forest height, the BM coefficients are nearly identical. The minimum BM coefficients are $BMCoeff_{min} = 0.00028$ at $x_2/H = 6$ for the forest with small clearing, $BMCoeff_{min} = 0.00025$ at $x_2/H = 4$ for the forest with wide clearing and $BMCoeff_{min} = 0.00014$ at $x/H = 4$ for the short forest.

The general curve progression agrees well with that observed by Stacey *et al.* (1994). Our values of the short forest are slightly higher near the leading edge than their values (their mean BM coefficient at $x/H = 0$ amounts to 0.008). This

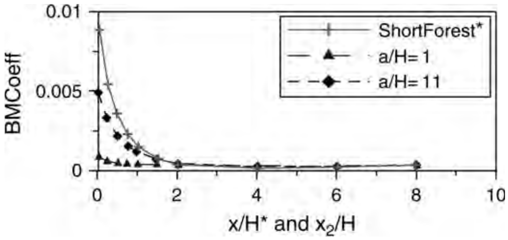


Figure 14. Mean BM coefficients as a function of downstream distance from the leading forest edge x/H.

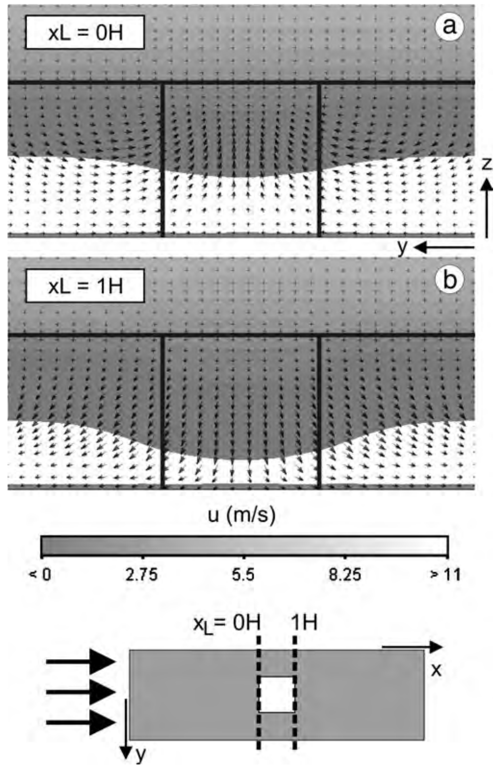


Figure 15. Mean velocity components of the 3D forest configuration with rectangular clearing: View in streamwise direction (*yz*-plane). Contour plots: *x*-velocity, vector plots: *y*- and *z*-velocities. The white areas in the lower part of the plots are regions with reverse flow ($u < 0$ m/s).

is perhaps mainly the consequence of the different stand heights and the different approach flow characteristics. A similar variation of the mean wind moment with distance from the leading forest edge was also observed by Yang *et al.* (2006b).

3D clearings of varying shape

As already mentioned, two 3D forest configurations with clearings of different shape were investigated: a rectangular clearing of size 1 $H \times$ 1 H and an (approximately) round clearing with a diameter of 1 H. For the rectangular clearing, contour and vector plots of the time-averaged velocity components are depicted for different lines of vision: view in streamwise direction (Figure 15), top view (Figure 16a) and side view (Figure 17b,c). The corresponding plots of the round clearing are very similar and hence only the top view is shown in Figure 16b.

As was shown in the previous section, the flow field above a 2D clearing of width 1 H is dominated by a recirculation zone extending over the entire clearing width (see also vector plot in Figure 17a). Similar recirculation zones occur above the two 3D clearings (Figure 17b,c). The air masses rotate around centres lying approximately in the middle of the clearing ($x_L = 0.4\ H - 0.5\ H$) at a height $z = 0.4\ H - 0.53\ H$. The exact positions of the centres of the recirculation zones are given in Figure 17. In comparison to the infinitely long clearing, the centre of the recirculation zone is shifted somewhat downstream and a little downwards in case of the rectangular clearing. Furthermore, the horizontal velocities are slightly higher and the absolute values of the vertical velocities are slightly lower at the centre of the rectangular clearing ($y/H = 0$) and both quantities are lower at the lateral clearing edge ($y/H = 0.5$) in comparison to the velocities in the 2D clearing (Figure 18). The differences between the infinitely long clearing and the rectangular clearing are, however, all in all small, especially at $y/H = 0$. This finding is in line with the observation of Stacey *et al.* (1994) that there is no significant difference in wind loading at the windward sides of holes or linear gaps of the same width.

Approaching the edges of the lateral forest areas in the 3D clearings, the intensity of the rotary motion decreases for $z < H$, viz. the absolute values of both u and w decrease with

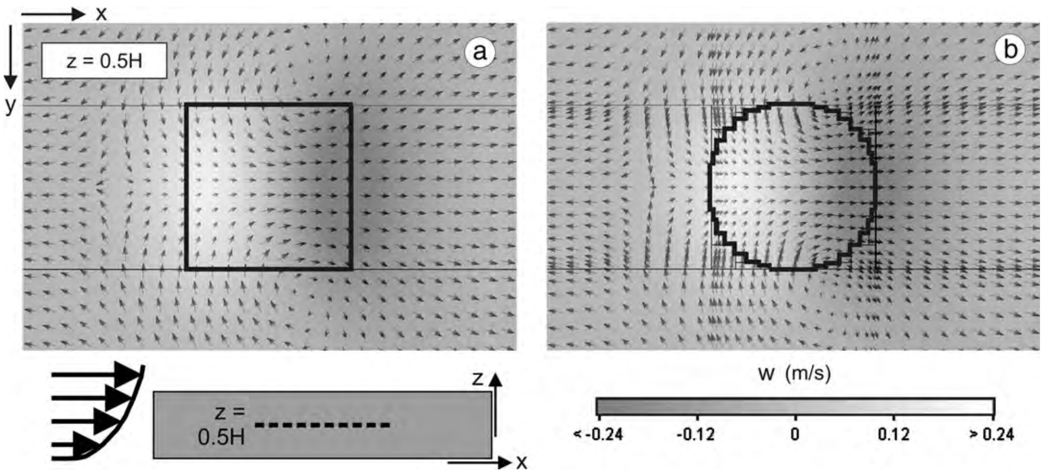
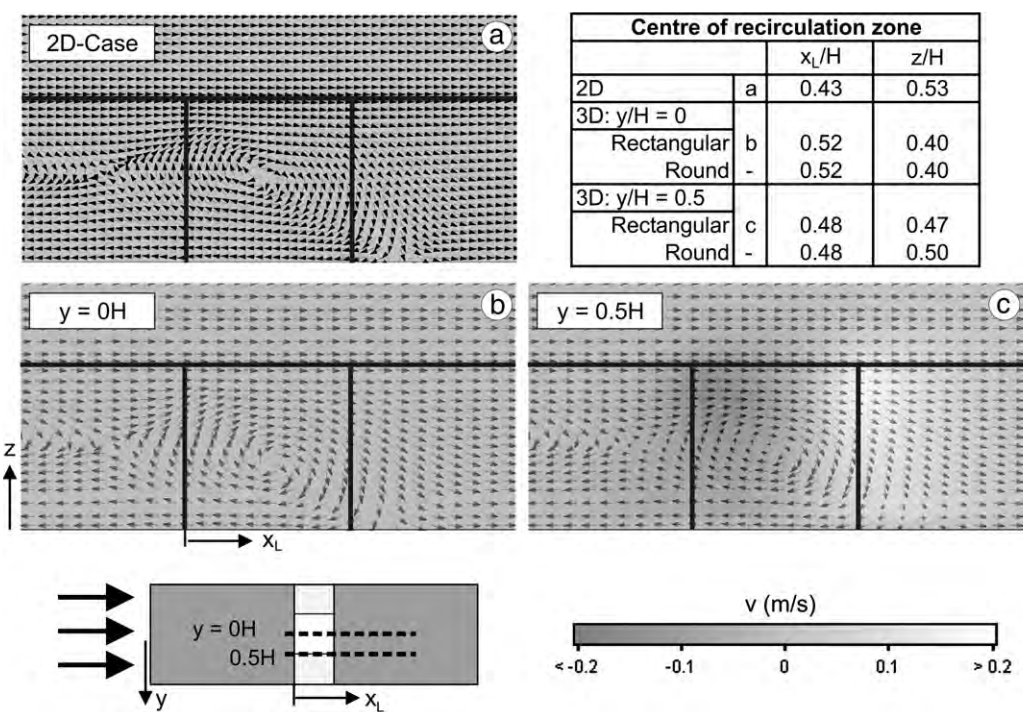


Figure 16. Mean velocity components of the 3D forest configurations with rectangular (a) and round (b) clearings: Top view (*xy*-plane). Contour plots: *z*-velocity, vector plots: *x*- and *y*-velocities.



Centre of recirculation zone			
		x_L/H	z/H
2D	a	0.43	0.53
3D: y/H = 0			
Rectangular	b	0.52	0.40
Round	-	0.52	0.40
3D: y/H = 0.5			
Rectangular	c	0.48	0.47
Round	-	0.48	0.50

Figure 17. Mean velocity components of the 2D forest (a) and the 3D forest configuration with rectangular clearing (b, c): Side view (*xz*-plane). Contour plots: *y*-velocity, vector plots: *x*- and *z*-velocities.

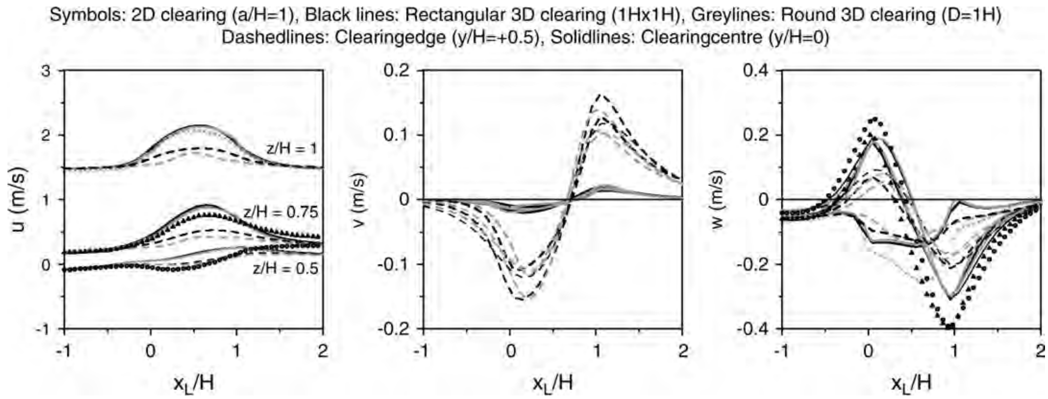


Figure 18. Horizontal profiles in *x*-direction of the mean velocity components *u* (left), *v* (middle) and *w* (right) at the clearing centre ($y/H = 0$, solid lines) and the lateral clearing edge ($y/H = 0.5$, dashed lines) for rectangular (black lines) and round (grey lines) 3D clearings. Symbols: 2D clearing.

increasing lateral distance from the clearing centre (Figure 18). At the same time, the centres of the recirculation zones are shifted slightly upwards (Figure 17).

In contrast to the 2D clearings (where v = 0 m/s), the lateral velocity component v of the 3D clearing configurations is not negligible, even if small. In the windward clearing region ($x_L < 0.7$ H), air flows from the lateral forest areas into the open space; in the leeward clearing region ($x_L >$ 0.7 H), the air flows in opposite direction, from the open space into the lateral forest areas (see Figures 15, 16 and 18).

The general flow pattern is not influenced by the clearing shape (Figure 16). As can be seen in Figure 18, the horizontal profiles of the velocity components u, v and w of the round and the rectangular clearings are nearly identical in the clearing centre (y/H = 0, solid lines) and vary only slightly at the lateral forest edges (y/H = +0.5, dashed lines). In the right-most position of the round clearing, the extreme values of the velocities are partly reduced and their positions are displaced slightly towards the streamwise clearing centre when compared with the rectangular clearing.

The numerical results show that there are only marginal differences between the flow fields above a round and a rectangular clearing. Unfortunately, no data from other studies are known to compare with our results from the square and round gaps.

Conclusions

The numerical CFD-Code, based on a LVEL k-ε model, can be used to a certain extent for a quantitative prognosis of the flow field around forests: Differences between computed and measured results occur mainly for the flow quantity TKE. The main reason for that lies in the limited possibilities to determine appropriate sink and source terms in the transport equations of both the TKE and the TDR. Nevertheless, the agreement between experimental and numerical results is all in all quite satisfactory for the mean velocity components.

The calculations of 2D clearings of varying width show that the clearing width has little influence on the flow field inside and above the upstream forest area, but affects strongly the flow field within and downstream of the clearing region. In comparison to the horizontal profiles in the wake of a short forest (being of equal length as the upstream forest area of the clearing configurations), the profiles within the clearing region are in general more curved as a result of the windward shelter effect of the downstream forest area. In the clearing region, the impact region of the latter interferes with the wake zone of the upstream forest area. For a/H = 1, the recirculation zone leeward of the upstream forest area extends over the entire clearing width. For the wider clearings, the reattachment length remains nearly constant ($x_{rez} \approx 2.8$ H) and the recirculation zones are displaced slightly downstream. The overall wind activity increases in the clearing region with increasing clearing width. With increasing clearing width, the entrainment of air into the lower region of the clearing ($z < H$) is augmented and, as a consequence, the volume flow rate through the leading edge of the downstream forest area increases likewise. Consequently, the flow pattern within the downstream forest area resembles more and more that inside the short forest configuration and the estimated mean BM coefficients of trees standing near the leeward clearing edges increase gradually.

It is a matter of common knowledge that trees adapt to the prevailing mean wind conditions. Thus, particularly in the case of newly created wide clearings, trees standing on the leeward clearing edge are exposed to unusually high wind loads and the storm damage risk of these trees will increase likely. Hence, clear-cut areas should be as small as possible in streamwise direction.

Furthermore, the numerical results show that there are only small differences between the flow fields of 2D and rectangular clearings of width $a/H = 1$. The differences between round and rectangular clearings are marginal likewise. Thus, it can be expected that there are only small differences in wind loadings on trees standing at the edges of such narrow clearings.

As stated in the introduction, the results within this series shall deliver information about the mean flow field around standard forest edge configurations. In a second and future step, the overlapping of transient gusts will be investigated in detail.

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Conflict of Interest Statement

None declared.

References

Belcher, S.E., Jerram, N. and Hunt, J.C.R. 2003 Adjustment of a turbulent boundary layer to a canopy of roughness elements. *J. Fluid Mech.* **488**, 369–398.

Bergen, J.D. 1975 Air movement in a forest clearing as indicated by smoke drift. *Agric. Meteorol.* **15**, 165–179.

Bergen, J.D. 1976 Windspeed distribution in and near an isolated, narrow forest clearing. *Agric. Meteorol.* **17**, 111–133.

Blenk, H. and Trienes, H. 1956 Strömungstechnische Beiträge zum Windschutz – Strömungsuntersuchungen an Windhindernissen am Modell und in der freien Natur. Grundlagen der Landtechnik. vol. 8, VDI—Verlag, Düsseldorf, Germany.

Dupont, S. and Brunet, Y. 2008 Edge flow and canopy structure: a large-eddy simulation study. *Bound. Layer Meteorol.* **126**, 51–71.

Finnigan, J. 2000 Turbulence in plant canopies. *Annu. Rev. Fluid Mech.* **32**, 519–571.

Flesch, T.K. and Wilson, J.D. 1999 Wind and remnant tree sway in forest cutblocks. I. Measured winds in experimental cutblocks. *Agric. For. Meteorol.* **93**, 229–242.

Flomerics Limited 2005 FLOVENT™ Instruction Manual for Software Version 6.1. Document Number: FLOVENT/IMN/1005/1/0.

Foudhil, H., Brunet, Y. and Caltagirone, J.-P 2005 A fine-scale k-ε model for atmospheric flow over heterogeneous landscapes. *Environ. Fluid Mech.* **5**, 247–265.

Frank, C. 2005 . Wirksamkeit von dünnen Windschutzstreifen auf Sockelwällen in luv- und leeseitiger Anordnung. Dissertation, Universitätsverlag Karlsruhe, 228.

Frank, C. and Ruck, B. 2005 Double-arranged mound-mounted shelterbelts: influence of porosity on wind reduction between the shelters. *Environ. Fluid Mech.* **5**, 267–292.

Frank, C. and Ruck, B. Windkanalstudie zur Strömung in Waldlichtungen. In *Proc. 15. GALA Fachtagung "Lasermethoden in der Strömungsmesstechnik," University of Rostock, September 2007, 9.1–9.9.*

Gardiner, B.A., Marshall, B., Achim, A., Belcher, R., and Wood, C. 2005 The stability of different silvicultural systems: a wind-tunnel investigation. *Forestry.* **78**, 471–484.

Gash, J.H.C. 1986 Observations of turbulence downwind of a forest-heath interface. *Bound. Layer Meteorol.* **36**, 227–237.

Green, S.R. 1992 Modelling turbulent airflow in a stand of widely-spaced trees. *Phoenics J. Comput. Fluid Dyn. Appl.* **5**, 294–312.

Katul, G.G., Mahrt, L., Poggi, D. and Sanz, C. 2004 One- and two-equation models for canopy turbulence. *Bound. Layer Meteorol.* **113**, 81–109.

Krzikalla, F. 2005 Numerical investigation of the interaction between wind and forest under heterogeneous conditions. University of Karlsruhe, Diploma thesis. 113.

Launder, B.E. and Spalding, D.B. 1974 The numerical computation of turbulent flows. *Comput. Methods Appl. Mech. Eng.* **3**, 260–289.

Li, Z., Lin, J.D. and Miller, D.R. 1990 Air flow over and through a forest edge: a steady-state numerical simulation. *Bound. Layer Meteorol.* **51**, 179–197.

Liu, J., Chen, J.M., Black, T.A. and Novak, M.D. 1996 E-ε modelling of turbulent air flow downwind of a model forest edge. *Bound. Layer Meteorol.* **77**, 21–44.

Morse, A.P., Gardiner, B.A. and Marshall, B.J. 2002 Mechanisms controlling turbulence development across a forest edge. *Bound. Layer Meteorol.* **103**, 227–251.

Miller, D.R., Lin, J.D. and Lu, Z.N. 1991a Air flow across an alpine forest clearing: a model and field measurements. *Agric. For. Meteorol.* **56**, 209–225.

Miller, D.R., Lin, J.D. and Lu, Z.N. 1991b Some effects of surrounding forest canopy architecture on the wind field in small clearings. *For. Ecol. Manage.* **45**, 79–91.

Raupach, M.R., Bradley, E.F. and Ghadiri, H. 1987 A Wind Tunnel Investigation into the Aerodynamic Effect of Forest Clearings on the Nesting of Abbott's Booby on Christmas Island. Internal Report, CSIRO Division of Environmental Mechanics, Canberra, Australia. 21.

Raynor, G.S. 1971 Wind and temperature structure in a coniferous forest and a contiguous field. *For. Sci.* **17**, 351–363.

Rudnicki, M., Mitchell, S.J. and Novak, M.D. 2004 Wind tunnel measurements of crown streamlining and drag relationships for three conifer species. *Can. J. For. Res.* **34**, 666–676.

Sanz Rodrigo, J., Van Beeck, J. and Dezsö-Weidinger, G. 2007 Wind tunnel simulation of the wind conditions inside bidimensional forest clear-cuts. Application to wind turbine siting. *J. Wind Eng. Ind. Aerodyn.* **95**, 609–634.

Sogachev, A. and Panferov, O. 2006 Modification of two-equation models to account for plant drag. *Bound. Layer Meteorol.* **121**, 229–266.

Stacey, G.R., Belcher, R.E., Wood, C.J. and Gardiner, B.A. 1994 Wind flows and forces in a model spruce forest. *Bound. Layer Meteorol.* **69**, 311–334.

Stull, R.B. 1988 An Introduction to Boundary Layer Meteorology. Kluwer Academic Publishers, Dordrecht, The Netherlands, 666.

Wilson, J.D. and Flesch, T.K. 1999 Wind and remnant tree sway in forest cutblocks. III. A windflow model to diagnose spatial variation. *Agric. For. Meteorol.* **93**, 259–282.

Yang, B., Raupach, M.R., Shaw, R.H., Paw, U.K.T. and Morse, A.P. 2006a Large-eddy simulation of turbulent flow across a forest edge. Part I: flow statistics. *Bound. Layer Meteorol.* **120**, 377–412.

Yang, B., Shaw, R.H. and Paw, U.K.T. 2006b Wind loading on trees across a forest edge: A large eddy simulation. *Agric. For. Meteorol.* **141**, 133–146.

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