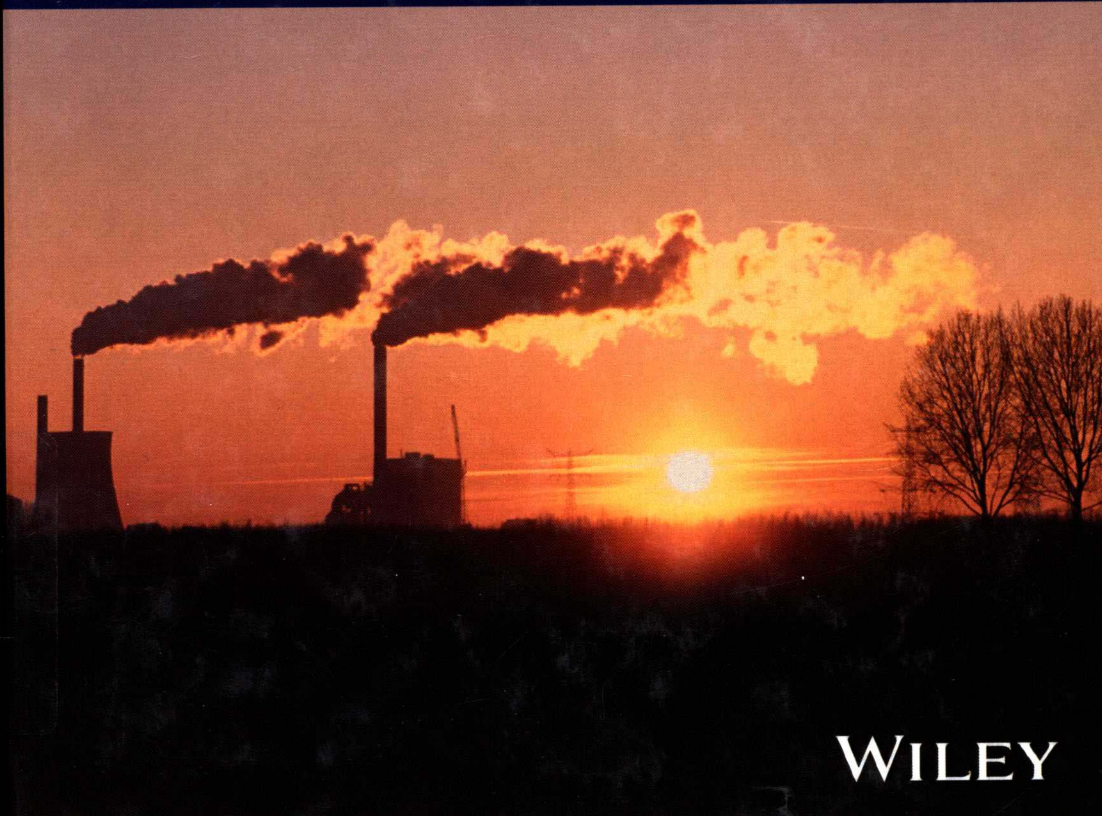
Air Dispersion Modeling

Foundations and Applications

Alex De Visscher



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To Julie

LIST OF SYMBOLS

a	acceleration ($m\ s^{-2}$)
	activity (–)
A	droplet surface area per unit air volume ($m^2\ m^{-3} = m^{-1}$)
	frequency factor [s^{-1} (first order); cm^3 $molecule^{-1}$ s^{-1} (second order)]
	absorbance (–)
A_f	frontal area (m^2)
A_p	plan area (m^2)
A_T	total area (m^2)
A_s	stack cross-sectional area (m^2)
B	Bowen ratio (–)
b_a	empirical constant ($m^2\ \mu g^{-1}$)
c	speed of light in vacuum ($m\ s^{-1}$)
	amount concentration or mass concentration ($mol\ m^{-3}$ or $g\ m^{-3}$)
C	Cunningham slip correction factor (–)
	number concentration ($molecules\ cm^{-3}$)
c_0	gas-phase concentration in equilibrium with the surface ($\mu g\ m^{-3}$)
C_0	Lagrangian structure function constant (–)
c_{air}	air-phase pollutant concentration ($\mu g\ m^{-3}$)
C_D	drag coefficient (–)
C_G	net radiation fraction going into the ground (–)
$c_{i,air}$	air-phase concentration of pollutant at interface ($\mu g\ m^{-3}$)
$c_{i,water}$	water-phase concentration of pollutant at interface ($\mu g\ m^{-3}$)
c_m	mass concentration ($g\ m^{-3}$)
c_{odor}	odor concentration ($ou\ m^{-3}$)
c_p	specific heat ($J\ kg^{-1}\ K^{-1}$)
$c_{p,air}$	specific heat of air ($J\ kg^{-1}\ K^{-1}$)
C_{vis}	visual contrast (–)
$C_{vis,x=0}$	visual contrast at zero distance (–)
c_w	droplet-phase pollutant concentration ($\mu g\ m^{-3}$)
c_{water}	water-phase pollutant concentration ($\mu g\ m^{-3}$)
C_x	yz plane integrated plume concentration ($g\ m^{-1}$)
cov()	covariance (product of units of correlating functions)
d	displacement height (m)
	day of the year (d)
d_p	particle diameter (m)
D	molecular diffusivity (gas phase) ($m^2\ s^{-1}$)
D_{ij}	binary diffusion coefficient of compound i in compound j ($m^2\ s^{-1}$)
D_w	molecular diffusivity (water phase) ($m^2\ s^{-1}$)
$\overline{e}$	turbulent kinetic energy ($m^2\ s^{-2}$)
E	activation energy ($J\ mol^{-1}$)
	irradiance ($W\ m^{-2}$ or $W\ cm^{-2}$)
e_p	photon energy ($J\ photon^{-1}$ or simply J)

E_p	photon irradiance (photons cm^{-2} s^{-1} or simply cm^{-2} s^{-1})
$E_{p,\lambda}$	spectral photon irradiance (photons cm^{-2} s^{-1} nm^{-1} or simply cm^{-2} s^{-1} nm^{-1})
E_λ	spectral irradiance (W m^{-2} nm^{-1} or W cm^{-2} nm^{-1})
f	Coriolis parameter (s^{-1})
F	deposition flux (μg m^{-2} s^{-1})
	broadening factor in falloff kinetics (–)
f_0	reactivity factor (–)
F_b	buoyancy flux parameter (m^4 s^{-3})
F_c	"complementary" (stochastic) force (N)
	falloff parameter (–)
F_d	pollutant flux at droplet surface (μg m^{-2} s^{-1})
	drag force (N)
F_m	momentum flux parameter (m^4 s^{-2})
f_y	dispersion factor in the y direction (–)
f_z	dispersion factor in the z direction (–)
Fr_H	Froude number for hill height (–)
Fr_W	Froude number for hill width (–)
g	acceleration of gravity (m s^{-2})
h	Planck constant (J s)
	effective source height (m)
	hour angle (rad or °)
	vertical thickness scale (m)
	denser-than-air plume height (m)
H	enthalpy (J)
	height of a hill (m)
	height of a building (m)
	dimensionless Henry constant (–)
h_a	average plume height (m)
H_c	height of the cavity (depends on location) (m)
H_{cp}	Henry constant on a concentration/pressure basis (mol m^{-3} Pa^{-1})
h_d	dividing streamline height (m)
h_{fh}	horizontal flame extent (m)
h_{fv}	vertical flame height (m)
h_{mix}	mixing layer height (m)
H_r	height of obstacles defining roughness (m)
H_R	height of the cavity at its maximum (m)
h_s	source height (m)
h_t	altitude of terrain (m)
H_W	height of the far wake (m)
$h*$	vertical height scale (m)
I	actinic flux (photons cm^{-2} s^{-1} nm^{-1} or simply cm^{-2} s^{-1} nm^{-1})
	ionic strength (mol kg^{-1})
$i_{background}$	light intensity of background
iF	intake fraction (–)
i_{object}	light intensity of object
i_u	turbulent intensity in the x direction (m)
i_v	turbulent intensity in the y direction (m)
i_w	turbulent intensity in the z direction (m)
J	mass flux (moving frame of reference) (g m^{-2} s^{-1})

j_i	photochemcial rate constant of reaction i (s^{-1})
k	von Kármán constant (–)
	Boltzmann constant (J $molecule^{-1}$ K^{-1} or J K^{-1})
K	equilibrium constant (–)
k_0	apparent second-order rate constant in low-pressure limit (cm^3 $molecule^{-1}$ s^{-1})
k_G	air-phase mass transfer coefficient (m s^{-1})
K_h	turbulent heat diffusivity (m^2 s^{-1})
k_i	rate constant of reaction i [(s^{-1} (first order); cm^3 $molecule^{-1}$ s^{-1} (second order)]
k_L	water-phase mass transfer coefficient (m s^{-1})
K_m	turbulent momentum diffusivity (m^2 s^{-1})
K_s	solubility constant (–)
K_x	turbulent mass diffusivity in the x direction (m^2 s^{-1})
K_y	turbulent mass diffusivity in the y direction (m^2 s^{-1})
K_z	turbulent mass diffusivity in the z direction (m^2 s^{-1})
k_∞	rate constant at high pressure limit (cm^3 $molecule^{-1}$ s^{-1})
L	Obukhov length (m)
	length of a building, projected along the wind direction (m)
l	path length (m or cm)
L_f	flame length (m)
L_I	integral length scale (m)
L_R	length of the cavity (m)
LAI	leaf area index (–)
m	mass (kg)
m_a	mass of ambient air (kg)
m_w	mass of water vapor (kg)
M	molar mass (g mol^{-1} or kg mol^{-1})
$\mathbf{M}$	variance–covariance matrix of velocity fluctuation matrix (m^2 s^{-2})
	material balance matrix (s^{-1})
M_{air}	molar mass of air (g mol^{-1} or kg mol^{-1})
M_c	pollutant molar mass (kg mol^{-1})
M_u	mass exchange rate constant between layers (s^{-1})
n	amount of substance (i.e., number of moles) (mol)
	fractional cloud cover (–)
	integrated stochastic perturbation function (m s^{-1})
N	mass flux (fixed frame of reference) (g m^{-2} s^{-1})
N_A	Avogadro constant (molecules mol^{-1} or mol^{-1})
N_{BV}	Brunt–Väisälä frequency (s^{-1})
N_i	flux of i in a fixed frame of reference (mol m^{-2} s^{-1})
n_{iA}	order of reaction i with respect to compound A (–)
ou	odor unit
p	pressure (Pa = kg m^{-1} s^{-2})
	probability density function of location and velocity (s m^{-2})
P	probability density function (inverse of units of the distributed variable)
p_0	pressure at the surface (Pa)
p_c	critical pressure (Pa)
p^*	nondimensionalized pressure (–)
$PM_{2.5}$	mass concentration of particulate matter smaller than 2.5 μm diameter (μg m^{-3})
q	heat (J = kg m^2 s^{-2})
	sensible heat flux (J m^{-2} s^{-1})

	water/air mass ratio (–)
	pollutant mass fraction (–)
Q	emission rate (g s^{-1})
q_A	anthropogenic heat flux (J m^{-2} s^{-1})
Q_c	heating value (kW)
q_G	heat flux into the ground (J m^{-2} s^{-1})
q_i	mass fraction of compound i (–)
q_L	latent heat flux (J m^{-2} s^{-1})
Q_{mdi}	downward mass flux between two layers (kg m^{-2} s^{-1})
Q_{mi}	exchanged mass flux between two layers (kg m^{-2} s^{-1})
Q_{mui}	upward mass flux between two layers (kg m^{-2} s^{-1})
Q_s	sensible heat emission (kW)
r	albedo (–)
r_a	aerodynamic resistance (s m^{-1})
r_{ac}	surface canopy resistance (s m^{-1})
r_b	quasi-laminar resistance (s m^{-1})
r_c	surface resistance (s m^{-1})
r_{cf}	foliar resistance (s m^{-1})
r_{cg}	ground resistance (s m^{-1})
r_{cl}	resistance of leaves, twigs, bark, … (s m^{-1})
r_{cut}	cuticle resistance (s m^{-1})
$r_{cut,d}$	dry cuticle resistance (s m^{-1})
$r_{cut,w}$	wet cuticle resistance (s m^{-1})
r_{cw}	water resistance (s m^{-1})
r_{dc}	canopy resistance
r_{fg}	correlation coefficient between f and g (–)
r_{gd}	dry ground resistance (s m^{-1})
r_{gw}	wet ground resistance (s m^{-1})
r_{gs}	ground resistance below surface canopy (s m^{-1})
r_i	resistance parameter (s m^{-1})
r_{lu}	cuticle resistance parameter (s m^{-1})
r_m	mesophyll resistance (s m^{-1})
r_{st}	stomatal resistance (s m^{-1})
R	ideal gas constant (J mol^{-1} K^{-1})
	solar radiation energy flux (J m^{-2} s^{-1})
	spread parameter in bi-Gaussian convective cycling model (–)
	building length scale (m)
	precipitation rate (mm h^{-1})
	atmospheric resistance (s m^{-1})
	reflection probability (–)
R_A	reaction rate of compound A (molecules cm^{-3} s^{-1})
R_i	reaction rate of reaction i (molecules cm^{-3} s^{-1})
R_L	Lagrangian autocorrelation coefficient (–)
R_N	net radiation energy flux (J m^{-2} s^{-1})
r_s	stack radius (m)
r_t	total resistance to deposition (s m^{-1})
R_{vv}	autocorrelation coefficient (–)
R'_{vv}	autocorrelation function (m^2 s^{-2})
Re	Reynolds number ($=du\rho/\mu=du/\nu$) (–)

Re_*	Reynolds number based on friction velocity ($=z_0 u_* \rho/\mu = z_0 u_*/\nu$) (–)
RH	relative humidity (%)
s	stability parameter (s^{-2})
	distance traveled by plume center (m)
S	skewness of vertical wind speed distribution ($m^3\ s^{-3}$)
S°	standard entropy (J mol^{-1} K^{-1})
S_r	spacing of obstacles defining roughness (m)
S'_{uu}	spectrum function of wind speed variance ($m^2\ s^{-1}$ if function of ν)
S_{uu}	normalized spectrum function of wind speed variance (s if function of ν or ω; m if function of κ)
S_w	saturation (–)
Sc	Schmidt number ($=\nu/D$)
t	time (s or h)
t_0	time of the solar noon (h)
$t_{1/2}$	half life (s)
T	temperature (K)
t_a	apparent time (s)
T_a	ambient temperature (K)
T_c	critical temperature (K)
T_i	integral time scale (s)
$T_{i,L}$	Lagrangian integral time scale (s)
T_s	stack gas temperature (K)
	surface air temperature (K)
T_v	virtual temperature (K)
u	wind speed in the x direction (m s^{-1})
U	wind speed in the X direction, Lagrangian frame of reference (m s^{-1})
	internal energy (J)
$\overline{u}$	average wind speed (m s^{-1})
u'	wind speed fluctuation (m s^{-1})
u_0	wind speed variable in nocturnal atmosphere stability calculations (m s^{-1})
u_1	wind speed in the x_1 (i.e., x) direction (m s^{-1})
u_2	wind speed in the x_2 (i.e., y) direction (m s^{-1})
u_3	wind speed in the x_3 (i.e., z) direction (m s^{-1})
U_a	ambient wind speed (m s^{-1})
U_{atm}	wind speed (m s^{-1})
u_c	characteristic velocity (m s^{-1})
U_c	wind speed in a cavity (m s^{-1})
u_{H_r}	wind speed at height H_r (m s^{-1})
U_{sc}	velocity of plume centerline (m s^{-1})
U_W	wind speed in a far wake (m s^{-1})
u_*	friction velocity (m s^{-1})
u_{*w}	water-side friction velocity (m s^{-1})
u_τ	local friction velocity (between obstacles) (m s^{-1})
v	wind speed in the y direction (m s^{-1})
V	wind speed in the Y direction, Lagrangian frame of reference (m s^{-1})
$\mathbf{V}$	velocity fluctuation matrix (m s^{-1})
$\overline{V}$	total wind speed (m s^{-1})
v_d	deposition velocity (m s^{-1})
v_s	settling velocity (m s^{-1})

v_t	transfer velocity (m s^{-1})
w	wind speed in the z direction (m s^{-1})
	work (J)
W	wind speed in the Z direction, Lagrangian frame of reference (m s^{-1})
	width of a hill (m)
	width of a building, projected across the wind flow (m)
	Wiener process
w_*	convective velocity (m s^{-1})
$\overline{w_1}$	average vertical wind speed of updrafts (m s^{-1})
$\overline{w_2}$	average vertical wind speed of downdrafts (m s^{-1})
w_b	emission velocity at the surface (m s^{-1})
W_c	half-width of the cavity (m)
	wet fraction of the cuticle (–)
w_e	entrainment velocity (m s^{-1})
W_g	wet fraction of the ground (–)
w_s	stack gas velocity in the vertical direction (m s^{-1})
W_{st}	wet fraction of the stomata (–)
w_w	water weight fraction of air (–)
W_W	width of the far wake (m)
w'_w	water–air weight ratio (–)
x	downwind distance from the source (m)
	coordinate in the west–east direction (Eulerian models) (m)
	distance from the upwind side of a building (m)
X	downwind distance coordinate, Lagrangian frame of reference (m)
x_1	coordinate in the west–east direction (Eulerian models) (m)
x_2	coordinate in the south–north direction (m)
x_3	vertical distance (m)
x_f	downwind distance to the source of final plume rise (m)
x_v	distance to virtual source (m)
x_{vis}	visibility (m)
y	crosswind distance from the plume axis (m)
	coordinate in the south–north direction (m)
Y	crosswind distance coordinate, Lagrangian frame of reference (m)
y_i	mole fraction of i in the gas phase (–)
z	vertical distance from the surface (terrain following coordiates) (m)
	vertical distance from the surface at the source (Cartesian coordinates) (m)
Z	vertical distance coordinate, Lagrangian frame of reference (m)
	vertical distance coordinate, terrain following coordinates (m)
z_0	roughness length (m)
z_j	junction height (m)

Greek letters

α	along-plume entrainment rate parameter (–)
	quasi-laminar layer thickness parameter (–)
	mass transfer enhancement factor (–)
α_a	absorption coefficient (m^{-1})
α_c	sea roughness parameter (–)
α_{ext}	extinction coefficient (m^{-1})

α_k	Kolmogorov constant (–)
α_s	scattering coefficient (m^{-1})
$\alpha_{s,air}$	scattering coefficient for air molecules (m^{-1})
$\alpha_{s,PM}$	scattering coefficient for PM (m^{-1})
β	ratio of Lagrangian to Eulerian integral time scales (–)
	across-plume entrainment rate parameter (–)
	parameter describing height dependence of density in denser-than-air plumes (–)
γ	vertical slope of potential temperature above the planetary boundary layer (K m^{-1})
	wavelength (m)
	activity coefficient
Γ	dry adiabatic lapse rate (K m^{-1})
Γ_s	moist adiabatic lapse rate (K m^{-1})
δ	solar declination (rad or °)
$\Delta_f H°$	standard enthalpy of formation (kJ mol^{-1})
Δh	plume rise (final) (m)
Δh_{sd}	stack downwash (m)
$\Delta_r G°$	standard Gibbs free energy of reaction (kJ mol^{-1})
$\Delta_r H°$	standard enthalpy of reaction (kJ mol^{-1})
$\Delta_r S°$	standard entropy of reaction (J mol^{-1} K^{-1})
ΔU	velocity deficit (m s^{-1})
$\Delta_{vap} H$	enthalpy of vaporization (J kg^{-1})
Δz	plume rise (transitional) (m)
$\Delta\theta$	temperature jump at capping inversion (K)
ε	height of obstacles defining surface roughness (m)
	energy dissipation rate (m^2 s^{-3})
	emissivity (–)
	molar decadic absorption coefficient (cm^2 $molecule^{-1}$ or simply cm^{-2})
ζ	dimensionless height variable in Monin–Obukhov theory (–)
η	Kolmogorov length microscale (m)
θ	potential temperature (K)
	dimensionless temperature variable (–)
	terrain slope (rad)
θ_C	temperature (°C)
θ_F	temperature (°F)
θ_m	vertical average potential temperature in mixing layer (K)
θ_v	virtual potential temperature (K)
θ_*	friction temperature (K)
κ	thermal diffusivity (m^2 s^{-1})
	wave number (rad m^{-1} or simply m^{-1})
λ	height scale for Coriolis effects (m)
	thermal conductivity (J m^{-1} K^{-1})
	latitude (rad or °)
	molecule mean free path (m)
	scavenging coefficient (s^{-1})
	wavelength (m or nm)
λ_1	area fraction of updraft (–)
λ_2	area fraction of downdraft (–)
λ_f	frontal area parameter (–)
λ_t	spatial Taylor microscale (m)

Λ_L	Lagrangian integral length scale (m)
λ_p	plan area parameter (–)
Λ	temperature lapse rate (K m^{-1})
	scavenging ratio (s^{-1})
μ	dynamic viscosity (Pa s)
ν	kinematic viscosity (m^2 s^{-1})
	frequency (s^{-1})
ρ	density (kg m^{-3})
ρ_a	ambient air density (kg m^{-3})
ρ_p	particle density (kg m^{-3})
ρ_s	stack gas density (kg m^{-3})
σ	Stefan–Boltzmann constant (s^{-1} m^{-2} K^{-4})
	absorption cross-section (cm^2 $molecule^{-1}$ or simply cm^2)
σ_n	standard deviation of perturbation function (m s^{-1})
σ_u	turbulent velocity in the x direction (m s^{-1})
σ_v	turbulent velocity in the y direction (m s^{-1})
σ_w	turbulent velocity in the z direction (m s^{-1})
σ_{w1}	turbulent velocity in the z direction of updraft (m s^{-1})
σ_{w2}	turbulent velocity in the z direction of downdraft (m s^{-1})
σ_x	dispersion parameter along the horizontal wind direction (m)
σ_y	dispersion parameter across the horizontal wind direction (m)
σ_z	dispersion parameter in the vertical direction (m)
τ	shear stress (Pa)
	time constant (s)
τ_0	shear stress at the surface (Pa)
τ_s	Taylor microscale (s)
φ	solar elevation (rad)
ϕ	latitude (rad)
	angle between plume path and the horizontal (rad)
	quantum yield (–)
ϕ_h	Monin–Obukhov similarity function for heat transfer (–)
ϕ_m	Monin–Obukhov similarity function for momentum transfer (–)
φ_y	dilution factor due to lateral dispersion (m^{-1})
φ_z	dilution factor due to vertical dispersion (m^{-1})
ω	angular frequency (rad s^{-1} or simply s^{-1})
Ω	angular velocity of Earth (s^{-1})

CONTENTS