Appendices

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Appendix A

Scaling Variables and Dimensionless Groups

Scaling Variables

Scaling variables are used in similarity theory to nondimensionalize other variables. The following tables summarize length, velocity, time, temperature and humidity scales. Detailed discussions of these variables and their applications are presented in the body of this book. See Appendix B for definitions of notation.

Dimensionless Groups

Sometimes, the ratio of terms from an equation has significance concerning the nature of turbulence in the boundary layer. For example, if one term represents the suppression of turbulence and another term represents the generation of turbulence, then the ratio of these two terms might give an indication of the existence of turbulence or its intensity. The ratio of such terms defines a dimensionless group.

The following tables present many of the dimensionless groups that are used in boundary layer meteorology.

Length Scales:

Symbol	Name	Dimensions	Definition	Characteristics & Use
z_i	Inversion height or ML depth	m	Average mixed layer depth	Convective BL
L	Obukhov length	m	$\frac{-\overline{\theta_v}\, u_*^3}{k\, g\, \overline{w'\theta_v'}_s}$	Surface layer scale
λ_{max}	Wavelength of peak in TKE spectrum	m	$1/\kappa_{max}$ or $2\pi/\kappa_{max}$	Dominant eddy size
z_o	Aerodynamic roughness length	m	Height where $\overline{u}=0$ in a log wind profile	Measure of the effective earth-surface roughness (surface layer)
$H_{\Delta\theta}$	Integral depth scale	m	$\int_{t_{sunset}}^{t} \overline{w'\theta'}_s \, d\tau / \Delta\overline{\theta}_s$	Stable (nocturnal) BL
η	Kolmogorov viscous length scale	m	$(\nu^3/\varepsilon)^{1/4}$	The largest eddies that feel the effects of viscosity
h_e	Ekman layer depth scale	m	u_* / f_c	Related to the depth of the idealized Ekman BL
L_L	Local Obukhov length	m	$\frac{-\overline{\theta}_v\, (\overline{u'w'}^2 + \overline{v'w'}^2)^{3/4}}{k\, g\, \overline{w'\theta'_v}}$	z - less scaling in the stable BL
W_H	Hill width	m	Hill width	Flow over hills and obstacles

Velocity Scales:

Symbol	Name	Dimensions	Definition	Characteristics & Use
w_*	Free-convection scaling velocity	m / s	$\left[\frac{g\, z_i}{\overline{\theta}_v}\,(\overline{w'\theta'_v})_s\right]^{1/3}$	Convection BL (used only when $(\overline{w'\theta'_v})_s \geq 0$)
u_*	Friction velocity	m / s	$\left(\overline{u'w'}_s^{\,2} + \overline{v'w'}_s^{\,2}\right)^{1/4}$	Surface layer and forced convection
$e^{1/2}$	TKE velocity scale	m / s	$(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})^{1/2}$	Eddy velocity
G	Geostrophic wind	m / s	$-\frac{1}{\overline{\rho}\, f_c}\frac{\partial \overline{p}}{\partial y}$	A measure of the pressure - gradient force
σ_u	Standard deviation of u	m / s	$(\overline{u'^2})^{1/2}$	Eddy velocity in x-direction
u_ε	Dissipation velocity scale	m / s	$(k\, z\, \varepsilon)^{2/3}$	Related to flow of TKE from large to small wave numbers
w_{Lf}	Local free convection velocity scale	m / s	$\left[\frac{g}{\overline{\theta}_v}\, z\, \overline{w'\theta'_v}\right]^{1/3}$	Bottom of the mixed layer
u_L	Local friction velocity scale	m / s	$\left(\overline{u'w'}^{\,2} + \overline{v'w'}^{\,2}\right)^{1/4}$	Top of the stable boundary layer
u_*^{ML}	Convective stress velocity scale	m / s	u_*^2 / w_*	Stress in a mixed layer

Time Scales:

Symbol	Name	Dimensions	Definition	Characteristics & Use
t_*	Free convection time scale	s	z_i / w_*	Time for a thermal to rise in convective BL
$1 / N_{BV}$	Oscillation time period (inverse Brunt - Väisälä frequency)	s	$\left(\frac{g}{\overline{\theta}_v} \frac{\partial \overline{\theta}_v}{\partial z} \right)^{-1/2}$	Buoyant oscillation period in statically stable environment. (used when $\partial \overline{\theta}_v / \partial z \geq 0$)
$1 / f_c$	Inertial period	s	$\left[(1.46 \times 10^{-4} s^{-1}) \sin(\phi) \right]^{-1}$	Related to earth's rotation. (Not used much any more in BL studies.)

Miscellaneous Scales:

Symbol	Name	Dimensions	Definition	Characteristics & Use
θ_*^{SL}	Surface-layer temperature scale	K	$\frac{-\overline{(w'\theta'_v)}_s}{u_*}$	Eddy temperature fluctuations in surface layer
θ_*^{ML}	Mixed-layer temperature scale	K	$\frac{\overline{(w'\theta'_v)}_s}{w_*}$	Eddy temperature fluctuations in convective BL
θ_L	Local surface-layer temperature scale	K	$\frac{-\overline{(w'\theta'_v)}}{u_L}$	Top of stable surface layer
θ_{Lf}	Local free convection temperature scale	K	$\frac{\overline{(w'\theta'_v)}}{w_{Lf}}$	Bottom of convective boundary layer
$\Delta\theta$	Temperature jump	K	$\theta_o - \theta_s$ or $\theta(z_i^+) - \theta(z_i^-)$	Stable boundary layer strength or capping inversion strength
q_*^{SL}	Surface-layer humidity scale	$\frac{g_{water}}{g_{air}}$	$\frac{-\overline{(w'q')}_s}{u_*}$	Eddy moisture fluctuations in surface layer
q_*^{ML}	Mixed-layer humidity scale	$\frac{g_{water}}{g_{air}}$	$\frac{\overline{(w'q')}_s}{w_*}$	Eddy moisture fluctuations in mixed layer
q_L	Local surface layer humidity scale	$\frac{g_{water}}{g_{air}}$	$\frac{-\overline{(w'q')}}{u_L}$	Top of stable surface layer
q_{Lf}	Local free convection humidity scale	$\frac{g_{water}}{g_{air}}$	$\frac{\overline{(w'q')}}{w_{Lf}}$	Bottom of convective boundary layer

Dimensionless Groups:

Symbol	Name	Definition	Characteristics & Use
Fr	Froude number	$\frac{M}{N_{BV} W}$	Flow characteristic past an obstacle of size W. (inertia / buoyancy) or (natural wavelength / physical wavelength)
Ra	Rayleigh number	$\frac{g\,(\Delta T)\,D^3}{\rho\,\nu\,\nu_\theta}$	Benard convection between 2 plates of separation D and temperature difference ΔT (not used in BL because Ra >> 0).
Re	Reynolds number	$\frac{M\,D}{\nu}$	Ratio of inertial to viscous forces. Indicates when statically neutral flow becomes turbulent. (not used in BL because Re >> 0).
Ri	Richardson number (gradient)	$\frac{(g/\overline{\theta}_v)\ \partial\overline{\theta}_v/\partial z}{(\partial\overline{u}/\partial z)^2+(\partial\overline{v}/\partial z)^2}$	Dynamic stability parameter. Indicates when laminar flow becomes turbulent.
R_f	Flux Richardson number	$\frac{(g/\overline{\theta}_v)\ \overline{w'\theta_v'}}{\overline{u'w'}\ \partial\overline{U}/\partial z\ +\ \overline{v'w'}\ \partial\overline{V}/\partial z}$	Dynamic stability parameter. Indicates when turbulent flow becomes laminar. Ratio of consumption to generation terms of TKE.
R_B	Bulk Richardson number	$\frac{g}{\overline{\theta}_v}\ \frac{\Delta\theta_v\ \Delta z}{(\Delta U)^2 \quad (\Delta V)^2}$	Approximation to the gradient Richardson number based on differences across distance Δz .
Ro	Surface Rossby number	$\frac{G}{f_c\,z_o}$	Ratio of pressure-gradient to friction (roughness). Used to estimate drag coefficients.

Dimensionless Groups:

Symbol	Name	Definition	Characteristics & Use
ϕ_M	Dimensionless wind shear	$\frac{kz}{u_*} \frac{\partial \overline{M}}{\partial z}$	Flux-profile relationships in the surface layer.
ϕ_H	Dimensionless lapse rate	$\frac{kz}{\theta_*^{ML}} \frac{\partial \overline{\theta_v}}{\partial z}$	Flux-profile relationships in the surface layer.
μ	μ (Ekman)	$\frac{k u_*}{f_c L}$	An internal stability parameter.
μ_i	μ_i (Mixed Layer)	$\frac{k z_i}{L}$	An internal stability parameter.
C_D	Drag coefficient	u_*^2 / M^2	Relates frictional drag to mean wind.
k	von Karman constant	$\lim_{z \to z_o} \left[\frac{-u_* \, \partial^2 \overline{u} / \partial z^2}{(\partial \overline{u} / \partial z)^2} \right]$	A "universal" constant related to turbulent flow near a surface ($k \approx 0.35$ to 0.41).
ζ	Zeta	z/L	An internal stability parameter (used in surface layer). ($\zeta \approx R_i$ in unstable conditions).
z/z_i	Fraction of the mixed layer height	z/z_i	Height within the mixed layer.
X^{ML}	Convective horizontal advection distance	$\frac{x \, w_*}{z_i \overline{M}}$	Actual horizontal distance traveled relative to one convective timescale distance.

Appendix B

Notation

A Note on Notation. Some notational compromises were required to avoid the conflicting definitions of symbols that appeared in the boundary-layer literature. For example, h is used for both moist static energy and boundary-layer depth, f for frequency and Coriolis parameter, and U for wind speed and wind component in the x-direction.

For some cases we resolved the conflicts by adding subscripts (e.g., f_c for Coriolis parameter). In other situations we extended existing classes of notation (e.g., s for both dry and moist static energies). Finally, in a few cases we had to define new symbols (e.g., M for wind magnitude).

A

a	albedo; various constants and parameters
a_c	bulk cloud albedo
a_{FR}	conductivity between air and ground in force-restore model
a_{IBL}	internal boundary layer parameter
agl	above ground level
A	various variables and constants; fundamental dimension of electric current; amplitude
A_R	an entrainment coefficient
A(k)	amplitude
A(t,x)	inverse Fourier transform
ABL	atmospheric boundary layer
ABLE	Amazon Boundary Layer Experiment
Am	amplitude spectrum
AMTEX	Air Mass Transformation Experiment

B

b	various constants and parameters
b_c	bulk cloud absorption
b_{IBL}	internal boundary layer parameter
B	various variables and constants; bulk measure of turbulence in the SBL
B_N	buoyant consumption of TKE
B_o	parameter for spectral diffusivity
B_P	buoyant production of TKE
B_{PN}	buoyancy
BAO	Boulder Atmospheric Observatory
BL	boundary layer
BLS77	Boundary Layer Structure 1977
BLX83	Boundary Layer Experiment 1983
BOMEX	Barbados Oceanography and Meteorology Experiment

C

c	pollutant or tracer concentration; generic constant
c_m	drag coefficient for individual roughness elements
$c_{n_{ref}}{}^2$	structure function parameter for index of refraction
$c_q{}^2$	structure function parameter for moisture
$c_{rh}{}^2$	structure function parameter for relative humidity
$c_T{}^2$	structure function parameter for temperature
$c_V{}^2$	structure function parameter for velocity
$c_A{}^2$	structure function parameter for variable A

C_D bulk momentum transfer coefficient (drag coefficient)
C_{Dh} drag coefficient at top of drainage flow
C_{DN} bulk momentum transfer coefficient for neutral conditions
C_E bulk moisture transfer coefficient
C_{EN} bulk moisture transfer coefficient for neutral conditions
C_g soil heat capacity
C_{GA} soil heat capacity per unit area
C_H bulk heat transfer coefficient (Stanton number)
C_{HN} bulk heat transfer coefficient for neutral conditions
C_p specific heat at constant pressure for moist air
C_{pd} specific heat at constant pressure for dry air
C_s speed of sound in air
C_* dimensionless canopy density
CAPE convective available potential energy
CAT clear air turbulence
CBL convective boundary layer
CCOPE Cooperative Convective Precipitation Experiment
CDT Central Daylight Time (CDT = UTC - 5 h)
CL cloud layer
Co cospectrum
Coh coherence spectrum
CPU central processing unit

D

d day; displacement distance
d_r day of the summer solstice
d_s depth of upper slab in force-restore model
d_y average number of days in a year
d_1 distance between the top of the ML and the height where the heat flux profile is zero
D nonlocal dissipation parameter; structure function; pipe diameter
D(L) structure function
$D_{AA}(r)$ structure function for variable A and itself
DFT Discrete Fourier Transform
Dis dissipation rate of TKE
Div horizontal divergence
DYCOMS Dynamics and Chemistry of Marine Stratocumulus

E

e instantaneous turbulence kinetic energy; water vapor pressure
e_{sat} saturation vapor pressure
E phase change rate (usually evaporation rate)
$E_A(n)$ discrete spectral intensity or energy of variable A
EAPE evaporative available potential energy
EZ entrainment zone

F

f frequency (often used for circular frequency in radians/s)
f_c Coriolis parameter
f_i intrinsic wave frequency
f_{max} frequency corresponding to peak in the spectrum
F momentum flux; discrete Fourier transform
F_{Ar} real part of the Fourier transform of variable A
F_{Ai} imaginary part of the Fourier transform of variable A
$F_A(n)$ discrete Fourier transform of variable A
F_u departure of the u-wind speed from geostrophic
F_v departure of the v-wind speed from geostrophic
F_w correction term in the Penman-Monteith Method
F_x generic flux
F_A^* complex conjugate of F_A
$F(t,\kappa)$ forward Fourier transform
FA free atmosphere
FASINEX Frontal Air Sea Interaction Experiment
FIFE First ISLSCP Field Experiment
FFT Fast Fourier Transform
Fr Froude number
Fr^* modified Froude number

G

g acceleration due to gravity
G geostrophic wind speed
G_A unfolded spectral energy of F_A
G_{AB} cross spectrum between variables A and B
G_s geostrophic wind speed at the surface

G_{z_i} geostrophic wind speed at the top of the boundary layer
G_2 wind scale within the upper boundary layer
GALE Genesis of Atlantic Low Experiment
GARP Global Atmospheric Research Program
GATE GARP Atlantic Tropical Experiment
GCM general circulation model
GW pressure-velocity correlation (and gravity waves)

H

h hour;
boundary layer depth;
depth of the stable boundary layer
h_d depth of the drainage flow
h_e Ekman layer depth
h_{eq} equilibrium SBL depth
h_i height of roughness element i
h_* average height of the canopy
h_o height of the bottom of the entrainment zone
h_2 height scale within the upper boundary layer;
height of the top of the entrainment zone
h^* average vertical extent of roughness elements
H SBL integral length scale (heat-flux-history scale);
height of obstacle
H_{eq} equilibrium SBL integral length scale
$H_{\Delta\theta}$ SBL integral depth scale
HAPEX Hydrologic-Atmosphere Pilot Experiment
HEXOS Humidity Exchange Over the Sea

I

I dimensionless turbulence intensity;
longwave radiation;
fundamental dimension of luminous intensity
I^* net longwave radiation
I^*_B net longwave radiative flux at the bottom of the cloud
I^*_h longwave radiative flux at the SBL top
I^*_s longwave radiative flux at the SBL bottom
I^*_T net longwave radiative flux at the top of the cloud

IBL internal boundary layer
IR infrared radiation
ISLSCP International Satellite Land Surface Climatology

J

J argument for wave function

K

k von Karman constant
k_g thermal molecular conductivity of the soil
K generic eddy diffusivity;
shortwave radiation;
fundamental temperature dimension
K^* net shortwave radiative flux
$K_B{}^*$ net shortwave radiative flux at the bottom of the cloud
$K_T{}^*$ net shortwave radiative flux at the top of the cloud
K_E eddy diffusivity for moisture
K_H eddy diffusivity for heat
K_m eddy diffusivity for momentum (eddy viscosity)
$K(\kappa)$ spectral turbulent diffusivity
K-H Kelvin-Helmholtz (waves)
KONTUR Convection and Turbulence over Sea

L

l mixing length
l_B buoyancy length scale
l_c distance travelled by negatively buoyant entrained elements
l_O Ozmidov scale
l_ε dissipation length scale
$l(r)$ structure buoyancy length scale
L Obukhov length;
time lag;
fundamental length dimension
L_f latent heat of fusion of water
L_L local Obukhov length
L_p latent heat associated with some phase change
L_s latent heat of sublimation of water
L_T length of straight line travelled in summing over i roughness elements
L_v latent heat of vaporization of water

L_X location parameter for lognormal distribution
L transilient mixing distance
L length scale
LCL lifting condensation level
LES large eddy simulation
LFC level of free convection
LLJ low-level jet
LOC limit of convection

M

m mass
msl (above) mean sea level
M magnitude of wind (wind speed); mass flux; fundamental mass dimension
M_s wind speed at the surface
M_{z_i} wind speed at the top of the boundary layer
MCC mesoscale cellular convection
METROMEX Metropolitan Meteorology Experiment
MKE kinetic energy associated with mean wind
ML mixed layer
MP mechanical production of TKE

N

n frequency (cycles per time period $\mathbb{P}$)
n_f Nyquist frequency
n_{ref} index of refraction
ñ frequency (cycles per second)
N number count
N_d cloud droplet number density
N_{BV} Brunt-Väisälä frequency
NBL nocturnal boundary layer

P

p pressure
p_0 reference pressure
pdf probability density function
P pressure
P_o reference pressure
P_{SP} saturation point pressure
$\mathbb{P}$ time period
PBL planetary boundary layer
PPI plan position indicator
Pr probability density
PRE-STORM Preliminary Regional Experiment of STORM-Central
PS process spectrum

Q

q specific humidity (of water vapor)
q_G specific humidity at the ground surface
q_L liquid water specific humidity; local humidity scale
q_{Lf} local free-convection humidity scale
q_s surface specific humidity of air
Δq_s moisture difference between air at the surface and aloft
q_T total water specific humidity
q_2 moisture scale in the upper boundary layer
q_* generic turbulent moisture scale
q_*^{ML} humidity scale for mixed layer, based on w_*
q_*^{SL} humidity scale for surface layer based on u_*
Q quadrature spectrum
Q_A effective bulk heat flux into the SBL associated with advection
Q_E latent heat flux
Q_g molecular heat flux within the ground
Q_G molecular heat flux within the ground at the surface
Q_H sensible heat flux
Q_R bulk heat flux
Q_T total heat flux acting on the SBL
Q_w effective bulk heat flux into the SBL
Q^* net radiation
Q_j^* component of net radiation in the j direction
ΔQ_S storage of internal energy

R

r mixing ratio; correlation coefficient
r spatial separation
r_a water vapor resistance through air
r_{AB} linear correlation coefficient between A, B
r_L liquid water mixing ratio
r_p total water vapor resistance of plant
r_T total water mixing ratio
r_{sat} saturation mixing ratio
$r'\theta'$ moisture temperature covariance
rh relative humidity

R moisture flux
$\Re$ gas constant for dry air
R(L) autocorrelation
$R_{AA}(L)$ autocorrelation of variable A with itself
R_B bulk Richardson number
R_c critical Richardson number for the onset of turbulence
R_f flux Richardson number
R_i Richardson number
R_T critical Richardson number for the termination of turbulence
R_v gas constant for moist air
Ra Rayleigh number
Re Reynolds number
RHI range height indicator
Ri gradient Richardson number
Ri^* convective Richardson number
RL residual layer
Ro surface Rossby number

S

s dry static energy
s_{cc} change of saturation specific humidity with temperature
s_e moist static energy
s_{es} saturation static energy
s_i horizontal surface area occupied by roughness element i
s_L liquid water static energy
s_s average vertical cross-section area presented to the wind by one roughness element
s_v virtual dry static energy
$s_A{}^2$ variance of variable A
s^2 variance
S spatial domain; solar irradiance (solar constant); spectral energy density
S_A spectral energy density of variable A
$S_A(n)$ spectral energy density of variable A
S_c net tracer body source term
S_G stability parameter
S_L ratio of total ground surface area to number of elements
S_q net moisture body source term; spectral energy density of moisture
S_{qT} net total water body source term
S_r area density of roughness element
S_{rT} net moisture body source term
S_T total area occupied by N roughness elements
S_X shape parameter for the lognormal distribution
$S(t,\kappa)$ spectral energy density
SBL stable boundary layer
SCL subcloud layer
SESAME Severe Environment Storms and Mesoscale Experiment
SL surface layer
SP saturation point

T

t time
t_o initial time
t_* time scale for the mixed layer
$t_*{}^{ML}$ time scale for the mixed layer
$t_*{}^{SL}$ surface-layer time scale (z/u_*)
T temperature (usually absolute temperature); fundamental time dimension
T_d dewpoint temperature
T_G temperature of upper slab in force-restore model
T_K net sky transmissivity
T_{LCL} temperature of parcel at the lifting condensation level
T_M temperature of lower slab in force-restore model
T_{SP} saturation point temperature
T_v virtual temperature (usually absolute)
TAMEX Taiwan Area Mesoscale Experiment
TDBU top down/bottom up (diffusion)
TIBL thermal (convective) internal boundary layer
TKE average turbulence kinetic energy
Tr turbulent transport across the spectrum
TS process spectra
TS(k,m) transport spectrum

U

u eastward moving Cartesian wind component; optical thickness
u_L local (friction) velocity scale
u_* friction velocity
$u_*{}^{ML}$ convective stress scale velocity

$u'w'$ kinematic flux of U-momentum in the vertical
U eastward moving Cartesian wind component
U_{eq} equilibrium wind speed
U_g eastward component of geostrophic wind
U_{gj} represents the components of geostrophic wind (U_g, V_g, 0)
U_i represents (U, V, W) for i = (1, 2, 3)
U_T generic transport velocity
UTC Coordinated Universal Time (virtually the same as GMT (Greenwich Mean Time) or Z time)

V

v northward moving Cartesian wind component
$v'w'$ kinematic flux of V-momentum flux in the vertical
V northward moving Cartesian wind component
V_B SBL buoyancy velocity scale
V_g northward component of geostrophic wind
V_M mechanical forcing scale
V velocity scale
VAD velocity-azimuth display
VIMEX Venezuelan International Meteorology and Hydrology Experiment

W

w upward moving Cartesian wind component (vertical velocity, negative for subsidence)
w_c average vertical velocity within the clouds at height z_i
w_e entrainment velocity
w_i longitudinal width of each roughness element i in the direction of travel
w_L mean large scale vertical motion acting at the top of the ML (subsidence)
w_{Lf} local free convection velocity scale
w_{up} average vertical velocity through active cloud bases
w_* convective velocity scale
$w'c'$ kinematic tracer flux in the vertical
$w'e$ vertical turbulent transport of TKE
$w'p'$ pressure correlation
$w'q'$ kinematic moisture flux in the vertical
$w'r'$ kinematic moisture flux in the vertical
$w's'$ kinematic vertical static energy flux
$w'T'$ kinematic temperature flux in the vertical
$w'\theta'$ kinematic potential temperature (heat) flux in the vertical
$w'\theta_v'$ kinematic virtual potential temperature (buoyancy) flux in the vertical
$w'\rho_v'$ kinematic vertical moisture flux
W width of obstacle; vertical velocity (same as w)
W_H width of the hill
W_P liquid water path
W_T length of obstacle disturbing the flow
$W_{1/2}$ half-width of the hill
$W(k)$ window weight

X

x Cartesian coordinate towards east (sometimes used in a coordinate system rotated such that x is aligned with the mean wind direction); location; generic distance; fetch
x_d coordinate parallel to mean wind
x_i represents (x, y, z) for i=(1, 2, 3)
X generic distance
X_s relative humidity of the air near the surface
X_G relative humidity at the ground surface
X^{ML} convective horizontal distance

Y

y Cartesian coordinate towards north (sometimes used as crosswind horizontal coordinate)
Y mixing potential

Z

z Cartesian coordinate up, relative to local sea-level horizontal surface
z_b cloud base height (top of the subcloud layer)
z_B height of cloud base
z_{hill} height of the hill
z_i average top of the mixed layer (base of the overlying temperature inversion)
z_{LFC} height of the level of free convection

z_{LOC} height of the limit of convection
z_{LW} depth of the column flowing over the hill
z_o aerodynamic roughness length
z_{o1} aerodynamic roughness length upwind of border
z_{o2} aerodynamic roughness length downwind of border
z_r top of the residual layer
z_T height of cloud top
Δz height above local terrain
Z_s scale of surface features or surface roughness
zo_{eff} effective roughness length

Greek

α terrain slope; various constants and parameters
α_c Charnock's parameter
α_{gM} angle between the surface and geostrophic wind
α_k Kolmogorov constant
α_{PT} Priestly-Taylor parameter
α_{ws} angle between the wind direction and the surface stress
β Bowen ratio; various parameters and constants
γ lapse rate ($\partial\theta_v/\partial z$); psychrometric constant (C_p/L_v)
γ_E Ekman spiral parameter ($([f_c/2K_m]^{1/2})$)
γ_T transilient mixing rate coefficient
$\gamma(t,\kappa)$ spectral component of spectral heat flux
Γ_d dry adiabatic lapse rate
δ depth of the internal boundary layer
δ_m unit vector
δ_{mn} Kronecker delta
δ_s solar declination angle
ε turbulence kinetic energy dissipation rate; ratio of dry air and water vapor gas constants
ε_c destruction rate of tracer concentration variance by molecular processes
ε_f infrared flux emissivity
ε_{fB} infrared flux emissivity from the bottom of the boundary layer
ε_{fT} infrared flux emissivity from the effective top of the atmosphere
ε_{ijk} alternating unit tensor
ε_{IR} emissivity in the infrared
ε_{mnq} alternating unit tensor
ε_q destruction rate of humidity variance by molecular processes
ε_R destruction rate of temperature variance by radiative processes
ε_{u_ic} destruction rate of tracer concentration by molecular processes
ε_{u_iq} destruction rate of moisture flux by molecular processes
$\varepsilon_{u_iu_k}$ destruction rate of momentum flux by molecular processes
ε_{uw} destruction rate of vertical flux of horizontal momentum by molecular processes
$\varepsilon_{u_i\theta}$ destruction rate of heat flux by molecular processes
ε_{wc} destruction rate of vertical tracer concentration flux by molecular processes
ε_{wq} destruction rate of vertical moisture flux by molecular processes
$\varepsilon_{w\theta}$ destruction rate of vertical heat flux by molecular processes
ε_θ destruction rate of temperature variance by molecular processes
ζ dimensionless height in the surface layer (z/L)
η Kolmogorov microscale for turbulence; radar reflectivity; net volumetric flow rate into a volume
η'' wave vertical displacement distance
θ potential temperature
θ_e equivalent potential temperature
θ_{es} saturation equivalent potential temperature
θ_G potential temperature at the ground surface
$\Delta\theta_h$ temperature jump at the top of the SBL
θ_L liquid water potential temperature; local temperature scale
θ_{Lf} local free-convection temperature scale
θ_{ML} potential temperature within the mixed layer
θ_s surface potential temperature of air

θ_v virtual potential temperature
θ_2 temperature scale within the upper boundary layer
θ_o initial potential temperature
θ_* generic turbulent temperature scale
θ_*^{ML} temperature scale for the mixed layer, based on w_*
θ_*^{SL} temperature scale for the surface layer, based on u_*
$\Delta\theta_s$ SBL surface cooling (strength of inversion)
$\Delta\theta_{seq}$ equilibrium SBL strength
$\Delta_{EZ}\theta_v$ potential temperature jump across the entrainment zone
κ wavenumber
κ_b large wavenumber bound on the buoyancy subrange
κ_H horizontal wavenumber
κ_{max} wavenumber corresponding to peak in turbulence spectrum
κ_x wavenumber in the x direction
κ_y wavenumber in the y direction
κ_z wavenumber in the z direction
λ wavelength
λ_e longitude
λ_{max} wavelength corresponding to peak in turbulence spectrum
λ_R wavelength of radar
λ_{sol} e-folding solar decay length
Λ empirical length scale parameter
μ dynamic viscosity
μ_B bulk viscosity
μ^{ML} mixed layer scaling parameter
μ^{SL} surface layer scaling parameter
ν kinematic molecular viscosity
ν_c kinematic molecular diffusivity for tracer constituent c in the air
ν_g soil thermal diffusivity
ν_q kinematic molecular diffusivity for water vapor in air
ν_θ kinematic molecular diffusivity for heat in air
ξ any variable
Ξ turbulent diffusivity transfer function
π 3.1415926535897932384626

π_i Pi group
ρ density
ρ_o reference density
ρ_v absolute humidity
σ standard deviation
σ_A fraction of the sky covered by active cumulus clouds
σ_c fractional cloud cover
σ_{c_H} fractional coverage of sky with high clouds
σ_{c_L} fractional coverage of sky with low clouds
σ_{c_M} fractional coverage of sky with middle clouds
σ_F fraction of the sky covered by forced cumulus clouds
σ_M standard deviation of variable M
σ_L total cumulus cloud cover
σ_P fraction of the sky covered by passive cumulus clouds
σ_{SB} Stefan-Boltzmann constant
σ_u standard deviation of U-wind
σ_w standard deviation of the vertical velocity
σ^2 variance
τ shear stress
τ_{ij} shear stress
τ_{mol} molecular stress
τ_R SBL response time
$\tau_{Reynolds}$ Reynolds stress
ϕ latitude
ϕ_E dimensionless moisture gradient in the surface layer
ϕ_H dimensionless potential temperature gradient in the surface layer
ϕ_M dimensionless wind shear in the surface layer
ϕ_r latitude of the Tropic of Cancer
$\phi(t,\kappa)$ spectral component of momentum flux
Φ phase shift angle; phase spectrum
χ pollutant (tracer) flux
Ψ solar elevation angle
Ψ_H surface layer stability correction term for heat
Ψ_M surface layer stability correction term for momentum
ω angular rotation rate of earth
ω^* convective mass flux
Ω angular velocity vector

Special Symbols and Operators

$\overline{(\ )}$	average operator
$\overline{\overline{(\ )}}$	average over a portion of the SBL depth
$\tilde{(\ )}$	normal (dynamic) flux (flux without tilda is a kinematic flux)
$(\ )'$	deviation from mean value
$(\ )''$	wave perturbation
$(\ )^+$	just above or greater than the value in parentheses
$(\ )^-$	just below or less than the value in parentheses
\\	phase-averaging operator
< >	average over the depth of the boundary layer
·	simple multiplication
•	vector dot product
×	vector cross product
∇	del operator
∇^2	Laplacian operator
∂	partial derivative
d	total derivative
Δ	difference
Δ_{EZ}	difference across the entrainment zone

Subscripts

g	within the ground; geostrophic
i,j,k,l,m,n,q	indices for summation notation (each index can take on the values 1, 2, or 3)
s	near surface air quantity
z_i	quantity at the top of the ML
B	bottom of cloud
G	at the ground surface
L	local scaling quantity; liquid water; low
T	top of cloud
*	scaling variable
o	initial or reference quantity
2	upper boundary layer scale

Superscripts

e	ensemble (average)
s	space (average)
t	time (average)
ML	mixed layer
SL	surface layer

Appendix C

Useful Constants, Parameters and Conversion Factors

Table C-1. Similarity "Constants"
(A range of values is also given for those cases where agreement has not been reached on the precise value.)

k	= 0.4 (range 0.35-0.41)	von Karman constant
α_k	= 1.53 - 1.68	Kolmogorov constant

Table C-2. Geophysical Parameters

g	= 9.8	$m \cdot s^{-2}$	acceleration due to gravity
r_e	= 6.37×10^6	m	average radius of earth
ω	= 2π radians / 24 h		rotation rate of earth
	= 7.27×10^{-5}	$(\text{radians}) \cdot s^{-1}$	
f_c	= $(1.46 \times 10^{-4}) \cdot \sin(\phi)$	s^{-1}	Coriolis parameter as a function of latitude (ϕ)
$\mathbb{P}_{inertial}$	= $12/\sin(\phi)$	h	inertial period

Table C-3. Radiation Parameters

S	= 1370	$W \cdot m^{-2}$	solar irradiance (i.e., solar constant)
	= 1.113	$K \cdot m \cdot s^{-1}$	(using sea-level air density for conversion)
σ_{SB}	= 5.67×10^{-8}	$W \cdot m^{-2} \cdot K^{-4}$	Stefan-Boltzmann constant

Table C-4. Parameters of Air

Values at sea level for a standard atmosphere:

ρ_{SL}	= 1.225	$kg\cdot m^{-3}$	standard density of air
	= 0.01225	$mb\cdot s^2\cdot m^{-2}$	
	= 0.001225	$kPa\cdot s^2\cdot m^{-2}$	
P	= 101.325	kPa	pressure
	= 1013.25	mb	
	= 1.013×10^5	$N\cdot m^{-2}$	
	= 82714	$m^2\cdot s^{-2}$	(in kinematic units)
T	= 288.15	K	temperature
	= 15	°C	
μ	= 1.789×10^{-5}	$kg\cdot m^{-1}\cdot s^{-1}$	dynamic molecular viscosity
ν	= 1.461×10^{-5}	$m^2\cdot s^{-1}$	kinematic molecular viscosity
k_θ	= 2.53×10^{-2}	$W\cdot m^{-1}\cdot K^{-1}$	molecular thermal conductivity
ν_θ	= 2.06×10^{-5}	$m^2\cdot s^{-1}$	molecular thermal diffusivity ($=k_\theta/\rho C_p$)
C_{pd}	= 1004.67	$J\cdot kg^{-1}\cdot K^{-1}$	specific heat of dry air at constant pressure
	= 1004.67	$m^2\cdot s^{-2}\cdot K^{-1}$	
C_p	= $C_{Pd}\cdot(1+0.84\cdot q)$	$m^2\cdot s^{-2}\cdot K^{-1}$	specific heat of moist air, for q in g/g.
$\Re$	= 287.04	$J\cdot K^{-1}\cdot kg^{-1}$	gas constant for dry air
	= 287.04	$m^2\cdot s^{-2}\cdot K^{-1}$	
	= 2.87	$mb\cdot K^{-1}\cdot m^3\cdot kg^{-1}$	
	= 0.287	$kPa\cdot K^{-1}\cdot m^3\cdot kg^{-1}$	

Dry air at other altitudes (standard atmospheric lapse rate assumed):

ρ_{100kPa}	= 1.212	$kg\cdot m^{-3}$	density of air at 111 m (where P = 100.0 kPa)
ρ_{1km}	= 1.112	$kg\cdot m^{-3}$	density of air at 1000 m (where P = 89.9 kPa)
ρ_{2km}	= 1.007	$kg\cdot m^{-3}$	density of air at 2000 m (where P = 79.5 kPa)

Air of other temperatures and humidities (at sea-level pressure):

ρ	= 1.292 & 1.289	$kg\cdot m^{-3}$	density of dry & saturated air	at 0°C
ρ	= 1.246 & 1.240	$kg\cdot m^{-3}$	density of dry & saturated air	at 10°C
ρ	= 1.204 & 1.194	$kg\cdot m^{-3}$	density of dry & saturated air	at 20°C
ρ	= 1.164 & 1.145	$kg\cdot m^{-3}$	density of dry & saturated air	at 30°C

Table C-5. Parameters of Liquid Water and Water Vapor

R_v	= 461.5	$J\cdot K^{-1}\cdot kg^{-1}$	gas constant for water vapor
$C_{p\ vapor}$	= 1875	$J\cdot kg^{-1}\cdot K^{-1}$	specific heat of water vapor
L_f	= 3.34×10^5	$J\cdot kg^{-1}$	latent heat of fusion (liquid:solid) at 0°C
L_s	= 2.83×10^6	$J\cdot kg^{-1}$	latent heat of sublimation (vapor:solid) at 0°C
L_v	= 2.50×10^6	$J\cdot kg^{-1}$	latent heat of vaporization (vapor:liquid) at 0°C.
L_v	= 2.45×10^6	$J\cdot kg^{-1}$	latent heat of vaporization (vapor:liquid) at 20°C.
L_v	$\cong [2.501 - 0.00237\cdot T(°C)] \times 10^6$	$J\cdot kg^{-1}$	latent heat of vaporization vs. T
ρ_{water}	= 1025	$kg\cdot m^{-3}$	density of liquid water
C_{water}	= 4200	$J\cdot kg^{-1}\cdot K^{-1}$	specific heat of liquid water
$(\rho\cdot C)_{water}$	= 4.295×10^6	$(W\cdot m^{-2}) / (K\cdot m\cdot s^{-1})$	heat capacity of liquid water

Table C-6. Conversion Factors and Combined Parameters

$\rho \cdot C_p$	$= 1.231 \times 10^3$	$(W \cdot m^{-2}) / (K \cdot m \cdot s^{-1})$	for air at sea level (conversion factor between dynamic and kinematic heat fluxes for dry air)
	$= 12.31$	$mb \cdot K^{-1}$	
	$= 1.231$	$kPa \cdot K^{-1}$	
$g / \Re$	$= 0.0342$	$K \cdot m^{-1}$	
$\Re / g$	$= 29.29$	$m \cdot K^{-1}$	
$\Re / C_{pd}$	$= 0.28571$	-	
$C_{pd} / \Re$	$= 3.50$	-	
$\Re / R_v$	$= 0.622$	$g_{water} \cdot g_{air}^{-1}$	$(\equiv \varepsilon)$
$\rho \cdot g$	$= 12.0$	$kg \cdot m^{-2} \cdot s^{-2}$	at sea level
	$= 0.12$	$mb \cdot m^{-1}$	
	$= 0.012$	$kPa \cdot m^{-1}$	
g / C_p	$= 0.00975$	$K \cdot m^{-1}$	dry adiabatic lapse rate (Γ_d)
	$= 9.75$	$K \cdot km^{-1}$	
C_p / g	$= 102.52$	$m \cdot K^{-1}$	
C_p / L_v	$= 4.0 \times 10^{-4}$	$(g_{water} \cdot g_{air}^{-1}) \cdot K^{-1}$	psychrometric "constant" (γ)
	$= 0.4$	$(g_{water} \cdot kg_{air}^{-1}) \cdot K^{-1}$	
L_v / C_p	$= 2.5$	$K / (g_{water} \cdot kg_{air}^{-1})$	to convert from a kinematic moisture flux to a kinematic latent heat flux
$\rho \cdot L_v$	$= 3013.5$	$[W \cdot m^{-2}] / [(g_{water} \cdot kg_{air}^{-1}) \cdot m \cdot s^{-1}]$	to convert from a kinematic moisture flux to a latent heat flux (sea level, standard atmosphere)

Table C-7. Typical surface conditions (based on Anthes, R.A., E.-Y. Hsie, and Y.-H. Kuo, 1987: Description of the Penn State/NCAR Mesoscale Model, version 4 (MM4). NCAR Tech Note NCAR/TN-282+STR, Boulder, CO 80307. 66pp). Summer/winter values are listed.

Landuse	Albedo (%)	Moisture Availability (%)	IR Emissivity (% at 9 μm)
Urban land	18/18	5/10	88/88
Agriculture	17/23	30/60	92/92
Range-grassland	19/23	15/30	92/92
Deciduous forest	16/17	30/60	93/93
Coniferous forest	12/12	30/60	95/95
Forest swamp	14/14	35/70	95/95
Water or ocean	8/8	100/100	98/98
Marsh or wetland	14/14	50/75	95/95
Desert	25/25	2/5	85/85
Tundra	15/70	50/90	92/92
Permanent ice	55/70	95/95	95/95
Tropical forest	12/12	50/50	95/95
Savannah	20/20	15/15	92/92

Table C-8. Soil and ground properties (Lettau, personal communication), where: ρ = density ($kg\cdot m^{-3}$), C = volumetric heat capacity ($10^6\ J\cdot m^{-3}\cdot K^{-1}$), and ν = thermal diffusivity ($10^{-6}\ m^2\cdot s^{-1}$).

Type	Composition	ρ	C	ν
Quartz sand	- dry	1500	1.24	0.24
	- 10% moisture	1650	1.54	1.22
	- 40% moisture	1950	2.76	0.91
Sandy clay	- 15% moisture	1780	2.42	0.38
Swamp land	- 90% moisture	1050	3.89	0.23
Rocks	- basalt	2800	2.34	0.66
	- sandstone	2600	2.30	1.13
	- granite	2700	2.13	1.28
	- concrete	2470	2.26	1.08
Snow	- new feathery	100	0.21	0.10
	- old packed	400	0.84	0.40
	- ice	920	2.05	0.92
Water	- still	1000	4.18	0.14

Appendix D

Derivation of Virtual Potential Temperature

Consider a volume (V) of cloudy air (saturated) with temperature T and total pressure P.

Let m_d = mass of dry air
m_v = mass of water vapor
m_L = mass of liquid water falling at terminal velocity

The density of the cloudy air is

$$\rho = \frac{m_d + m_v + m_L}{V}$$

$$= \rho'_d + \rho'_v + \rho'_L \qquad \text{"partial densities"}$$

where $\rho'_d = \dfrac{m_d}{V}$ $\quad \rho'_v = \dfrac{m_v}{V}$ $\quad \rho'_L = \dfrac{m_L}{V}$

Using the ideal gas law:

$$\rho'_d = \frac{P'_d}{\Re\, T} \quad \text{and} \quad \rho'_v = \frac{e_{sat}}{R_v T}$$

where e_{sat} = saturation vapor pressure

But $P'_d = P - e_{sat}$ Dalton's law of partial pressures

And $e_{sat} = \dfrac{r_{sat}}{r_{sat} + \varepsilon}\, P$ where $\varepsilon = \dfrac{\Re}{R_v} = 0.622$

$$\rho_d' = \frac{P - e_{sat}}{\Re\ T} = \frac{P\left(1 - \frac{r_{sat}}{r_{sat} + \varepsilon}\right)}{\Re\ T}$$

where $r = \frac{m_v}{m_d}$ = mixing ratio and

r_{sat} = saturation mixing ratio

$$\rho_v' = \frac{e_{sat}}{R_v T} = \frac{\varepsilon\, e_{sat}}{\Re\ T} = \frac{P\varepsilon\left(\frac{r_{sat}}{r_{sat} + \varepsilon}\right)}{\Re\ T}$$

$$\rho_L' = \frac{m_L}{V} = \frac{m_L}{m_d}\,\frac{m_d}{V} = r_L \rho_d'$$

Hence

$$\rho = \frac{(1 + r_L)\,P\left(1 - \frac{r_{sat}}{r_{sat} + \varepsilon}\right)}{\Re\ T} + \frac{P\varepsilon\left(\frac{r_{sat}}{r_{sat} + \varepsilon}\right)}{\Re\ T}$$

$$\rho = \frac{P}{\Re\ T}\left(\frac{\varepsilon}{r_{sat} + \varepsilon}\right)\left[1 + r_L + r_{sat}\right]$$

Define a virtual temperature T_v such that T_v is the temperature that dry air must be in order to have the same density as the moist air.

$$\boxed{\rho \equiv \frac{P}{\Re\ T_v}}$$

Thus:

$$T_v = T\left(\frac{r_{sat} + \varepsilon}{\varepsilon}\right)\frac{1}{\left[1 + r_L + r_{sat}\right]}$$

Doing the long division:

$$\left(\frac{1-\varepsilon}{\varepsilon}\right)$$

$$\begin{array}{lllllll}
 & 1 \;+\; \left(\frac{1-\varepsilon}{\varepsilon}\right) r \;-\; r_L & & & & & \\
\varepsilon + \varepsilon r + \varepsilon r_L \;\big) & \varepsilon \;+\; r & & & & & \\
\text{Eliminate } \varepsilon: & \varepsilon \;+\; \varepsilon r & + \varepsilon r_L & & & & \\
\hline
 & r(1-\varepsilon) & - \varepsilon r_L & & & & \\
\text{Eliminate } r: & r(1-\varepsilon) & + & + & (1-\varepsilon) r_L r & + (1-\varepsilon) r^2 & \\
\hline
 & & - \varepsilon r_L & - & (1-\varepsilon) r_L r & - (1-\varepsilon) r^2 & \\
\text{Eliminate } r_L: & & - \varepsilon r_L & - & \varepsilon r_L r & & - \varepsilon r_L^2 \\
\hline
\text{Remainder:} & & & - & (1+2\varepsilon) r_L r & - (1-\varepsilon) r^2 & + \varepsilon r_L^2
\end{array}$$

All terms in the remainder are on the order of r^2.

Therefore neglect the remainder because $r \ll 1$, leaving $r^2 \ll r$.

$$T_v \cong T\left[1 + \left(\frac{1-\varepsilon}{\varepsilon}\right) r_{sat} - r_L\right]$$

$$\boxed{T_v \approx T\,(1 + 0.61\, r_{sat} - r_L)}$$

Similarly — liquid water loading

$$\boxed{\theta_v \approx \theta\,(1 + 0.61\, r_{sat} - r_L)}$$

If unsaturated, then $r_L = 0$ and use r instead of r_{sat} :

$$\boxed{T_v \approx T\,(1 + 0.61\, r)}$$

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