Atmospheric Boundary Layers I

Lecture by Gert-Jan Steeneveld
(Thanks to Bert Holtslag and Leo Kroon)

Contents

Some Basics of Atmospheric Turbulence

Turbulent kinetic energy and fluxes

The surface energy balance
Learning objectives

After this lecture you know:

The definition or description of the boundary layer

Why the boundary layer is turbulent

The two driving mechanisms behind mixing in the boundary layer

Reynolds decomposition and how to use this technique to estimate heat and momentum fluxes

The contrast behind turbulence during day- and night time.

The implication of turbulence for the vertical profiles of temperature, humidity and other scalars.

The role of the land surface on the boundary layer

Why the wind speed increases logarithmically with height
Atmospheric Boundary layer (ABL)

The lower layer of the Atmosphere influenced by the presence of the earth’s surface: Friction, Surface Heating (Convection) and Cooling

Daytime ABL: 500-2000 m
Nighttime ABL: 10-500 m

Important characteristics: Diurnal Cycle over Land and Turbulence
Why do we study the atmospheric boundary layer?

We live in this layer!

- Weather: Temperature, Wind, Fog, Visibility,…
- Climate: Impact of Changing Conditions?
- Air Quality: Dispersion of Pollutants (Health) and Greenhouse gases
- Relevant for Agriculture, Energy demand, Traffic, Urbanization

Davy et al
Turbulence vs Laminar

- **Laminar flow:** steady, straight
- **Turbulent flow:** fluctuating, chaotic


Source: www.rededgelimages.com
Laboratory water flow past a cylinder
(Karman Vortex streets) Fig 9.2a
Breakdown of laminar flow into turbulence in a water tank (Fig 9.3)
Boundary layer with Cu flowing passing Madeira

https://www.youtube.com/watch?v=LfDyIB6J8kM
Observations of temperature fluctuations at several heights over flat terrain (Fig 9.6)

Sonic anemometer and thermometer for observing high frequency fluctuations
Statistical description of Turbulence

Reynolds’ decomposition

\[ C = \overline{C} + C' \]

\( \overline{C} \): Average

\( C' \): Fluctuation \( \overline{C}' \equiv 0 \)

See also MetClip 10
Statistical description of Turbulence

Reynolds’ decomposition

\[ T \]

\[ \bar{T} = 272.6 \]

\[ T' = T - \bar{T} \]

\[ \bar{T}' = 0 \]
Statistical description of Turbulence

$A' \neq 0$

$A' = 0$

$B' = 0$

$A'B'$: Covariance of $A$ and $B$
Statistical description of Turbulence

Reynolds’ decomposition

\[ A = \bar{A} + A' \]
\[ B = \bar{B} + B' \]

\[ \bar{A}\bar{B} = (\bar{A} + A') \times (\bar{B} + B') \]

\[ \bar{A}\bar{B} = \bar{A}\bar{B} + \bar{A}B' + A'\bar{B} + A'B' \]

\[ \bar{A}\bar{B} = \bar{A}\bar{B} + 0 + 0 + A'B' \]

\[ \bar{A}\bar{B} = \bar{A}\bar{B} + A'B' \]

\[ A'B' \]: Covariance of \( A \) and \( B \)
Statistical description of Turbulence

\[ w = \bar{w} + w' \]

\[ T = \bar{T} + T' \]

\[ \bar{wT} = \bar{wT} + \bar{w'T'} \]

\[ H = \rho c_p \bar{w'T'} \]

\[ \bar{w'T'}: \text{turbulent sensible heat flux} \]
Turbulent sensible heat flux

\( \frac{\partial T}{\partial z} < 0 \)

Day time

\( w' > 0 \)
\( T' > 0 \)
\( w'T' > 0 \)
Turbulent sensible heat flux

\[ \frac{\partial T}{\partial z} < 0 \]

\[ w' < 0 \]

\[ T' < 0 \]

\[ w'T' > 0 \]
Turbulent sensible heat flux

\[ \frac{\partial T}{\partial z} > 0 \]

\[ w' > 0 \]
\[ T' < 0 \]
\[ w'T' < 0 \]

Night time
Turbulent sensible heat flux

\[ \frac{\partial T}{\partial z} > 0 \]

Night

\[ w' < 0 \]

\[ T' > 0 \]

\[ w'T' < 0 \]
Sensible heat flux: $H$ [Wm$^{-2}$]

Night: $\frac{\partial T}{\partial z} > 0$

$H = \rho c_p w'T'$

$\tau = \rho w'u'$

$LE = \rho L_v w'q'$

$F = \rho w'CO_2'$

Night: $H < 0$

Day: $\frac{\partial T}{\partial z} < 0$

Day: $H > 0$
For vertical heat flux we should use potential temperature rather than actual temperature!

(Fig 9.8)
Turbulent heat flux / Sensible heat flux

\[
\overline{w \theta} = \overline{(w + w')(\theta + \theta')} = \overline{w \theta} + \overline{w' \theta'}
\]

\[\overline{w} \approx 0\] near surface, thus:

\[\overline{w \theta} \approx \overline{w' \theta'}\]

Sensible heat flux

\[
H = \rho C_p \overline{w' \theta'}
\]

\[
\frac{W}{m^2} = \frac{kg}{m^3} \frac{J}{m \cdot K} \frac{m}{s} = \frac{J}{sm^2}
\]

Turbulent heat flux

\[
\frac{Km}{s} \quad \text{“kinematic units”}
\]
Large Eddy Model Simulation of Convection: vertical heat exchange

\[ \Theta_{\text{ini}} = 292.5 \text{K} \]

Courtesy: Chiel van Heerwaarden
Large Eddy Model Simulation of Convection: vertical moisture exchange

$q_{\text{ini}} = 5 \text{ g/kg}$

Courtesy: Chiel van Heerwaarden
Spectrum of turbulence kinetic energy and the turbulence cascade (Fig 9.5)

“Big whirls have little whirls, That feed on their velocity; And little whirls have smaller whirls, and so on to viscosity”

(L.F. Richardson, 1928; see book p. 19)

Eddies size of boundary-layer depth to smallest scale of about 1 mm! (Kolmogorov scale)
A unique research facility in the Netherlands to sense the boundary layer (operated by KNMI)
Example: Cabauw tower observations 4 November 2006 (diurnal cycle of potential temperatures at 2 to 200 m)

Intense daytime turbulent mixing gives same potential temperature, but nighttime surface cooling leads to strong vertical gradients!
Cumulus Clouds above the tops of invisible thermals (Fig 9.4)
Daytime convective boundary layer

Strong mixing leads to almost uniform profiles, in particular for temperature (also due to entrainment at top)

(Figure by John Wyngaard, 1985)
Budget equation for potential temperature after Reynolds decomposition

\[
\frac{d\bar{\theta}}{dt} \equiv \frac{\partial \theta}{\partial t} + U \frac{\partial \theta}{\partial x} + V \frac{\partial \theta}{\partial y} + W \frac{\partial \theta}{\partial z} = - \frac{\partial w' \theta'}{\partial z} \quad \ldots
\]

Turbulent flux divergence

Similar equations for wind and any ‘conserved’ quantity \( C \) (specific humidity, momentum, tracers, \ldots)
Daytime convective boundary layer

\[
\frac{d \overline{\theta}}{dt} = - \frac{\partial \overline{w' \theta'}}{\partial z} = - \frac{(w' \overline{\theta}_{top} - w' \overline{\theta'}_{surface})}{z_i} \approx 1.2 \frac{w' \overline{\theta'}_{surface}}{z_i}
\]
Daytime convective boundary layer

How long does it take for an eddy to go around in the ABL?

\[ H = 100 \text{ W/m}^2 (0.081 \text{ K m/s}); \ Z_i = 1000 \text{ m} \]
Daytime convective boundary layer

Measure for mixing by convective turbulence

\[ w_*)^3 \equiv \frac{g}{\theta_v} \frac{\theta_s'}{w'} z_i = \frac{9.81}{300} \cdot 0.081 \cdot 1000 = 2.65 \]

\[ w_* \equiv 1.4 \text{ m/s} \]

Typical time scale

\[ t_* = \frac{z_i}{w_*} = \frac{1000}{1.4} \approx 12 \text{ min} \]
Break
Turbulence by friction only, surface cooling stabilizes: Large Gradients in Temperature and Wind

(Figure by John Wyngaard, 1985)
Stable boundary layers occur frequently and are often shallow.

(Stewart et al., 2012; Davy et al., 2015)
Shallow boundary layers show larger temperature trends (2m virtual temperatures from ERA-Interim, 1979-2014)

\[
\frac{d\bar{\theta}}{dt} = -\frac{\partial \bar{w}' \bar{\theta}'}{\partial z} \approx \frac{w' \bar{\theta}'_{\text{surface}}}{h}
\]

Lower depth h gives higher temperature rate for given surface heat flux

Impacts on Arctic temperature increase:

Arctic amplification

(Davy and Esau, 2016)
Shallow boundary layers impact on air quality, visibility and quality of life

Chinese women wear masks as haze from smog caused by air pollution hangs over the Forbidden City in Beijing. Photograph: Kevin Frayer/Getty Images
Turbulence statistics

Reynolds decomposition

\[ u'(t) = U(t) - \bar{U} \]

\[ \bar{u}' = 0 \quad \text{and} \quad \bar{U} = \frac{1}{N} \sum_{1}^{N} U \]

\[ \sigma_{u}^{2} = \frac{1}{N} \sum (U - \bar{U})^2 = \frac{1}{N} \sum (u')^2 \]

\[ = \bar{u}'^2 \neq 0 \]

Also for \( v, w, \theta, q \) and other conserved variables
Turbulent kinetic energy

\[
\frac{TKE}{m} = 0.5(\sigma_u^2 + \sigma_v^2 + \sigma_w^2)
\]

Per unit mass, compare with mean kinetic energy: \(0.5mV^2\)

\[\sigma_u, \sigma_v, \sigma_w = f(z, h, \ldots)\]

(h is boundary-layer depth)

Typically decrease with height

Isotropy \(\sigma_u^2 = \sigma_v^2 = \sigma_w^2\)
Momentum flux

\[
\text{cov}(u, w) = \frac{1}{N} \sum (U - \bar{U})(W - \bar{W})
\]

\[
= \frac{1}{N} \sum (u')(w') = u'w'
\]

Covariance represents a flux of momentum in this case (or drag force per unit area)!

\[
\tau_s = \rho (u'w'^2 + v'w'^2)^{1/2}
\]

At surface

\[
N / m^2 = (kg / m^3)(m / s)^2
\]

\[
\frac{\tau_s}{\rho} \equiv u_*^2
\]

\[u_*: \text{friction velocity (m/s)}\]

Measure for mechanical turbulence
Momentum flux and friction velocity
(neutral conditions: no stability effects)

Flux = Diffusivity x Gradient

\( u^2_* \equiv -u'w' = K_M \frac{dU}{dz} \)

\( K_M = \kappa u_* z \)

Von Karman constant \( \sim 0.4 \)

\( \frac{dU}{dz} = \frac{u_*}{\kappa z} \)
The log-law (law of the wall)

\[ \frac{dU}{dz} = \frac{u_*}{\kappa z} \]

Integration gives:

\[ U(z) = \frac{u_*}{\kappa} \ln \left( \frac{z}{z_0} \right) \]

\[ \frac{u_*}{U(z)} = \frac{\kappa}{\ln \left( \frac{z}{z_0} \right)} \]

Roughness length \( z_0 \)

(Neutral) Drag coefficient

\[ C_{DN} \equiv \left( \frac{u_*}{U_z} \right)^2 = \frac{\kappa^2}{\left( \ln \left( \frac{z}{z_0} \right) \right)^2} \]
Classification of roughness and landscape characteristics

<table>
<thead>
<tr>
<th>$z_0$ (m)</th>
<th>Classification</th>
<th>Landscape</th>
<th>$C_{DN}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0002</td>
<td>Sea</td>
<td>Calm sea, paved areas, snow-covered flat plain, tide flat, smooth desert.</td>
<td>0.0014</td>
</tr>
<tr>
<td>0.005</td>
<td>Smooth</td>
<td>Beaches, pack ice, morass, snow-covered fields.</td>
<td>0.0028</td>
</tr>
<tr>
<td>0.03</td>
<td>Open</td>
<td>Grass prairie or farm fields, tundra, airports, heather.</td>
<td>0.0047</td>
</tr>
<tr>
<td>0.1</td>
<td>Roughly open</td>
<td>Cultivated area with low crops and occasional obstacles (single bushes).</td>
<td>0.0075</td>
</tr>
<tr>
<td>0.25</td>
<td>Rough</td>
<td>High crops, crops of varied height, scattered obstacles such as trees or hedgerows, vineyards.</td>
<td>0.012</td>
</tr>
<tr>
<td>0.5</td>
<td>Very rough</td>
<td>Mixed farm fields and forest clumps, orchards, scattered buildings.</td>
<td>0.018</td>
</tr>
<tr>
<td>1.0</td>
<td>Closed</td>
<td>Regular coverage with large size obstacles with open spaces roughly equal to obstacle heights, suburban houses, villages, mature forests.</td>
<td>0.030</td>
</tr>
<tr>
<td>$\geq$2</td>
<td>Chaotic</td>
<td>Centers of large towns and cities, irregular forests with scattered clearings.</td>
<td>0.062</td>
</tr>
</tbody>
</table>

Logarithmic wind profile for neutral conditions

\[ U(z) = \frac{u_*}{\kappa} \ln \left( \frac{z}{z_0} \right) \]

Friction velocity
Von Karman constant
Roughness length

Wind profile in the statically-neutral surface layer, for a roughness length of 0.1 m. (a) linear plot. (b) semi-log plot.
How is turbulence produced?

**Turbulence production by wind shear**

\[ S = u_*^2 \frac{\partial U}{\partial z} = \frac{u_*^3}{kz} \]

**Turbulence production by Buoyancy**

\[ B = \frac{g}{\theta_v} w' \theta' \]
How is turbulence produced?

Buoyancy is negative in stable conditions!

\[ S = u_*^2 \frac{\partial U}{\partial z} = \frac{u_*^3}{kz} \]

\[ B = \frac{g}{\theta_v} \frac{w' \theta'}{<0} \]
Dynamic stability: B/S

\[
S = u_\ast^2 \frac{\partial U}{\partial z} = \frac{u_\ast^3}{kz} \quad B = \frac{g}{\theta_v} w' \theta'
\]

\[
\frac{B}{S} = \frac{g}{\theta_v} \frac{w' \theta'}{u_\ast^3} \frac{kz}{\theta_v} \equiv - \frac{z}{L}
\]

\[
L \equiv - \frac{u_\ast^3 \theta_v}{kg w' \theta'} \quad (- \text{sign for historical reasons})
\]

Obukhov length scale \(L\) as measure for dynamic stability:

\(L < 0: \text{unstable and } L > 0: \text{stable}\)

Below ILI mechanical (shear) turbulence dominates
Turbulence drives the boundary layer

Turbulence is generated by wind shear and buoyancy

Turbulence generates mixing and friction

Wind shear is always a source of turbulence

- Unstable conditions (buoyancy supports mixing)

- Stable conditions (negative buoyancy limits mixing)

Buoyancy is related to surface and radiation energy budget!
Radiation components at clear skies over land in summer (Fig 9.9)

\[ F^* = \text{net radiation available to the surface (}=Q^*) \]
\[ (s=\text{solar and } l=\text{longwave components}) \]
Surface energy budget (Fig 9.11)

Energy fluxes at vegetated land surface
day (lhs) and night (rhs)
Surface energy budget (Fig 9.11)

Energy fluxes at vegetated land surface day (lhs) and night (rhs)

Alternative notation: \( Q^* = LE + H + G \)

Bowen ratio: \( H/LE \)
Typical diurnal cycle of energy budget terms over land (Fig 9.10)

Alternative notation: $Q^* = LE + H + G$

Bowen $\sim 1/3$
Energy fluxes in desert daytime conditions

**Oasis:** Advection of warm and dry air over a cool and moist surface enhances evaporation.

Reverse sign of sensible heat flux (Stable!)
Radiation components at cloudy skies over land
Wageningen (www.wageningenur.nl/maq)

Radiation 1

Monday 21-01-2019

![Radiation Graph](image-url)
Diurnal cycle of sensible and latent heat flux at Wageningen Veensteeg weather station

Flux (half hour mean)

Data points marked by Eddypro quality flag:
- flag = 0 (good)
- flag = 1 (questionable)
- flag = 2 (bad)
Surface fluxes and bulk transfer coefficients

Recall (Neutral) Drag Coefficient

\[ C_{DN} \equiv \left( \frac{u_\ast}{U_z} \right)^2 = \frac{K^2}{(\ln(z/z_0))^2} \]

Generally for momentum

\[ \frac{\tau}{\rho} \equiv u_\ast^2 = C_D U_z^2 \]

For sensible heat

\[ \frac{H}{\rho C_p} = w' \theta_s' = C_H U_z (\theta_s - \theta_a) \]

For latent heat

\[ \frac{LE}{\rho L} = w' q_s' = C_E U_z (q_s - q_a) \]
Variation of bulk transfer coefficients for drag ($D$), heat ($H$) and moisture ($E$) with wind speed over ocean (Fig 9.13)
Boundary layer is turbulent due to wind shear and convection.

Reynolds decomposition is a tool to quantify turbulence.

Turbulence is strong during day and weaker during night.

The boundary layer undergoes a clear diurnal cycle over land.

Variables are well-mixed in daytime ABL, but not at night.

Characteristics of the underlying surface have strong impact!

In part II on Monday much more on Boundary Layers, its vertical structure, evolution and special terrain effects (sea, forests and cities).

Tomorrow: Reynolds decomposition in practice, solving the ABL budget for special case, estimating solar radiation (daytime)