1. Planetary Boundary Layer and clouds
   - Definition
   - PBL vertical structure
   - BL Clouds
     - Shallow convection clouds
     - Deep convective clouds
     - Marine Stratocumulus
   - PBL in complex terrain

2. Probing PBL turbulence
   - PBL equations
   - Probing PBL turbulence
   - Turbulence statistics
     - Approach, turbulence moments
     - Integral scales – autocorrelation function
     - Turbulent Kinetic Energy - turbulence spectra
     - Sampling errors
   - Estimating PBL processes
     - Flux vertical profiles
     - PBL growth
     - Entrainment
     - PBL scaling

3. Flying strategies
   - Needs for turbulence measurements
   - Vertical structure
   - Horizontal spatial variability
   - Thin interfaces
   - Clouds
Lecture I – 1h
Boundary Layer and clouds

Marie Lothon
Laboratoire d'Aérologie, Toulouse

Photo by M. Scherrer
Diurnal cycle of the surface and low troposphere

Definition of the planetary boundary layer (PBL)

Figure 3. Diurnal cycle of the components of the surface energy budget in cloudless conditions at a rural midlatitude site.

Courtesy of B. Campistron

Courtesy of R. Hogan
Surface forcing

(a) Daytime over moist surface
(b) Nighttime over moist surface
(c) Daytime over dry surface (Desert)
(d) Dry air over moist surface (Oasis)

Wallace and Hobbes, 2006
Two important ways to consider the PBL and clouds:

(1) Vertical structure / Evolution
(2) Spatial variability / Scales
PBL
vertical structure

Stull, 1988
Wallace and Hobbes, 2006
Courtesy of Colbert et al, 2008
Rolls

See also Lemone, 1973
and Weckwerth et al, 1997
<table>
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<th>Reference</th>
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<th>0 &lt; (-z/L) &lt; 21 (Grossman 1982)</th>
<th>Wind &gt; 5 m s(^{-1}) (Christian 1987)</th>
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Tropopause

Free troposphere

Inversion

Shallow convection

Courtesy of Colbert et al, 2008
Atmospheric moist convection

Stevens, 2005
Marine Stratocumulus

GOES Channel 1
July 24 2001 – 1200 UTC – DYCOMS RF07
Main processes in the stratocumulus-topped marine boundary layer (STBL)

- SW radiation
- Turbulent mixing
- Entrainment
- Cloud microphysics
Conceptual diagram for the stratocumulus-topped PBL
Stevens, 2007
VERTICAL STRUCTURE OF THE STBL

4 profiles made within a 4-hour period

RF07
July 24
Pockets and Open cells in stratocumulus clouds
Pockets and Open cells
Stevens et al, 2005
Pockets and Open cells

Van Zanten et al, 2005
Structure of the Trade Cumuli

Stevens, 2006
PBL in complex terrain

\[ F_r = \frac{U}{Nh} \]

\[ F_{r}^{*} = \frac{U}{N(Z_i - h)} \]

Wallace and Hobbes, 2006
Lenticular cloud
Banner cloud

formation of banner clouds

(a) plan view

(b) side view

 Courtesy of Bart Geers
Lecture II – 1h
Probing boundary layer turbulence

Atmosphere after Turbulent Mixing
Resolving Navier-Stokes equation with perturbations

\[ u = \langle u \rangle + u' \]

Momentum equations,

\[
\frac{\partial \langle u \rangle}{\partial t} + \langle u \rangle \frac{\partial \langle u \rangle}{\partial x} + \langle v \rangle \frac{\partial \langle u \rangle}{\partial y} + \langle w \rangle \frac{\partial \langle u \rangle}{\partial z} - f \langle v \rangle = -\frac{1}{\rho} \frac{\partial \langle p \rangle}{\partial x}
\]

\[-\frac{1}{\rho} \left[ \frac{\partial \langle \rho u' u' \rangle}{\partial x} + \frac{\partial \langle \rho u' v' \rangle}{\partial y} + \frac{\partial \langle \rho u' w' \rangle}{\partial z} \right] + \nu \nabla^2 \langle u \rangle,
\]

\[
\frac{\partial \langle w \rangle}{\partial t} + \langle u \rangle \frac{\partial \langle w \rangle}{\partial x} + \langle v \rangle \frac{\partial \langle w \rangle}{\partial y} + \langle w \rangle \frac{\partial \langle w \rangle}{\partial z} = -\frac{1}{\rho} \frac{\partial \langle p \rangle}{\partial z}
\]

\[+ \frac{\langle \theta \rangle}{\theta_0} - \frac{1}{\rho} \left[ \frac{\partial \langle \rho u' w' \rangle}{\partial x} + \frac{\partial \langle \rho v' w' \rangle}{\partial y} + \frac{\partial \langle \rho w' w' \rangle}{\partial z} \right] + \nu \nabla^2 \langle w \rangle,
\]

Adiabatic thermodynamics energy equation,

\[
\frac{\partial \langle \theta \rangle}{\partial t} + \langle u \rangle \frac{\partial \langle \theta \rangle}{\partial x} + \langle v \rangle \frac{\partial \langle \theta \rangle}{\partial y} + \langle w \rangle \frac{\partial \langle \theta \rangle}{\partial z} = -\langle w \rangle \frac{d\theta_0}{dz}
\]

\[+ \left[ \frac{\partial \langle u' \theta' \rangle}{\partial x} + \frac{\partial \langle v' \theta' \rangle}{\partial y} + \frac{\partial \langle w' \theta' \rangle}{\partial z} \right],
\]
A possible closure:

\[
< u'w' > = -K_m \frac{\partial < u >}{\partial z}, \quad < v'w' > = -K_m \frac{\partial < v >}{\partial z}
\]

and

\[
< \theta'w' > = -K_h \frac{\partial < \theta >}{\partial z},
\]

>> Importance of measuring turbulent variables,
To check, suggest and improve parameterizations
Probing turbulence from the ground

Figure 3.1: Taylor’s hypothesis (Stull 1988)

\[ \frac{d \xi}{dt} = 0 \]
\[ \frac{\partial \xi}{\partial t} + \bar{U} \cdot \nabla \xi = 0 \]
\[ \frac{\partial \xi}{\partial t} = -u \frac{\partial \xi}{\partial x} - v \frac{\partial \xi}{\partial y} - w \frac{\partial \xi}{\partial z} \]

Distance/time/frequency equivalence

\[ d = U t \]
\[ k = \frac{2\pi v}{U} \]
Probing turbulence from an aircraft

**Distance/time equivalence**

\[ d = U_a t \]

\[ k = \frac{2\pi \nu}{U_a} \]

\[ U_a : \text{Airplane True Airspeed} \]

! Concepts of « Transverse » and « Longitudinal » are different than when measuring from the ground!
In situ measurements of the air motion with an aircraft

\[ \vec{v} = \vec{v}_p + \vec{v}_a \]

- \( u = -U_a \sin(\psi + \beta) + u_p \)
- \( v = -U_a \cos(\psi + \beta) + v_p \)
- \( w = -U_a \sin(\theta - \alpha) + w_p \)

\(~1\text{ m/s}\) \(~100\text{ m/s}\) \(~0.01\) \(~1\text{ m/s}\)

Lenschow, RAF Bulletin #23
Definition and measurements of PBL turbulent processes

Content:

Statistics
Integral scales
Fluxes
Entrainment
Turbulent kinetic energy
Higher-order moments
Example of measured air vertical velocity time series
Example of measured air temperature time series
Statistical approach

\[ \sigma_{\xi}^2 = \frac{1}{(N-1)} \sum_{i=0}^{N-1} (\xi_i - \bar{\xi})^2 \]

If \( N \) is large enough \( \left( \frac{1}{(N-1)} \approx \frac{1}{N} \right) \), the variance will be:

\[ \sigma_{\xi}^2 = \frac{1}{N} \sum_{i=0}^{N-1} (\xi_i - \bar{\xi})^2 \]

Substituting \( \xi_i = \xi_i + \xi_i' \):

\[ \sigma_{\xi'}^2 = \frac{1}{N} \sum_{i=0}^{N-1} (\xi_i')^2 = (\bar{\xi'})^2 \]

\[ \text{covar}(\xi, \zeta) = \frac{1}{N} \sum_{i=0}^{N-1} (\xi_i - \bar{\xi}) \cdot (\zeta_i - \bar{\zeta}) = \frac{1}{N} \sum_{i=0}^{N-1} (\xi_i' \cdot \zeta_i') = \bar{\xi'} \cdot \bar{\zeta'} \]

\[ r_{\xi \zeta} = \frac{\bar{\xi'} \cdot \bar{\zeta'}}{\sigma_{\xi} \cdot \sigma_{\zeta}} \]
Higher-order moments

Variance

\[ \sigma_w^2 = \langle w^2 \rangle \]

3rd moment

\[ \mu_3 = \langle w^3 \rangle \]

Skewness

\[ S = \frac{\mu_3}{\sigma^3} \]

4th moment

\[ \mu_4 = \langle w^4 \rangle \]

Kurtosis

\[ K = \frac{\mu_4}{\sigma^4} \]
The autocovariance function of vertical velocity $w$ is defined as

$$R_w(r) \equiv \int_{-\infty}^{\infty} w(r')w(r' + r)dr',$$

(1)

where $r$ is the displacement. The integral scale, which is a measure of the length over which $w$ is relatively well correlated with itself, is defined as

$$l_w = \int_0^\infty \frac{R_w(r)}{R_w(0)}dr.$$  

(2)

$l_w$ can be estimated from the maximum of the running integral of (2):

$$l_w(r) \equiv \left[ \int_0^r \frac{R_w(r')}{R_w(0)}dr' \right]_{\text{max}},$$

(3)

which is reached at the first zero crossing of $R_w(r)$.
Integral scale

$L_w = 195 \text{ m}$
Energy density spectrum

Vertical velocity energy spectrum

\[ F_w(f) = \text{FFT}(w(t)) \]

\[ S_w(f) = F_w(f)F_w^*(f) \]

\[ S_w(f) = \text{FFT}(R_w(\tau)) \]

\[ R_w(\tau) = \text{IFFT}(S_w(f)) \]
Turbulent Kinetic Energy

\[
\bar{e} = \frac{1}{2} \left( \sigma_u^2 + \sigma_v^2 + \sigma_w^2 \right)
\]

\[
S_w(k) = \frac{4}{3} \alpha \varepsilon^{2/3} k^{-5/3}
\]

Stull, 1988
Wallace and Hobbes, 2006

\[
\frac{\partial \bar{e}}{\partial t} = \frac{g}{\theta_v} w' \theta'_v - \left( w'u' \frac{\partial \bar{u}}{\partial z} + w'v' \frac{\partial \bar{v}}{\partial z} \right) - \frac{\partial w'e'}{\partial z} - \frac{1}{\rho_0} \frac{\partial w'p'}{\partial z} - \varepsilon
\]

Production terms (buoyancy and shear) transport pressure dissipation

Kolmogorov constant

Dissipation rate (units: \(m^2 s^{-3}\))
Sampling errors

\[ F = \lim_{T \to \infty} \frac{1}{T} \int_{0}^{\infty} w'(t)s'(t)dt \equiv \frac{1}{N} \sum_{i=0}^{N} w'(i)s'(i) \]

Systematic error \(~10\%\)
Associated for example with limited leg or high pass filtering

\[ F - \langle F(L) \rangle \approx \frac{2FL_{ws}}{L} \]

Random error \(10\) to \(>50\%\)

\[ \frac{\sigma_F(T)}{|F|} = \left( \frac{2T_f}{T} \right)^{1/2} \left( \frac{1 + r_{ws}^2}{r_{ws}^2} \right)^{1/2} \]

Instrumental error \(<5\%\)

Lenschow, 1994
Mann and Lenschow, 1994
Figure 16: w, t, wt timeseries.
Interpretation of kinematic eddy fluxes
(Wallace and Hobbs 2006)

Stull, 1988
Wallace and Hobbes, 2006
Probing the Sahelian boundary layer

Water vapour mixing ratio

Potential temperature

Courtesy of G. Canut, 2010
Cloud edges
Buoyancy flux vertical structure

![Diagram showing buoyancy flux vertical structure](image_url)

*Courtesy of G. Canut, 2010*
Vertical profiles of the fluxes in the Sahelian boundary layer

Canut et al, 2010
Boundary layer growth and warming

encroachment

entrainment

\[ \Delta \theta_{vh} = \frac{1}{2} \gamma \theta h \]

Garratt, 1992
Entrainment rate

$$\beta = -\frac{w'\theta'_v|_i}{w'\theta'_v|_0}$$

Entrainment velocity

$$w_e = \frac{\partial Z_i}{\partial t} - w_h$$

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<th>Zero-order model (ZOM)</th>
<th>First-Order Model (FOM)</th>
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<td>$$w_e \sim -\frac{w' s'</td>
<td>_i}{\Delta s}$$</td>
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Estimating entrainment from aircraft measurements

\[ \beta = -\frac{\overline{w'\theta'_v}|_i}{\overline{w'\theta'_v}|_0} \]

\[ w_e \simeq -\frac{\overline{w's'}|_i}{\Delta s} \]
Boundary layer growth and warming

\[ \Delta \theta_v = \frac{\gamma \beta Z_i}{1 + 2\beta} \]

\[
\frac{\partial \overline{\theta_v}}{\partial t} = - \frac{\partial \overline{w'\theta_v'}}{\partial z} \\
= \frac{\overline{w'\theta_v'}|_0 - \overline{w'\theta_v'}|_i}{Z_i}
\]

\[ w_e = (1 + 2\beta) \frac{\overline{w'\theta_v'}|_0}{\gamma Z_i} \]
Boundary layer scaling

Deardoff velocity scale (Turbulent mixing during free convection)

\[ w^* = \left[ \frac{g z_i}{T_v} \frac{w'}{\theta'_s} \right]^{\frac{1}{3}} \sim 1 \text{ m/s} \]

\((z_i, \theta'_s)\): Depth of the BL and potential temperature perturbation at surface.

Friction velocity (Statically neutral conditions):

\[ u^* = \left( u'^2 + v'^2 \right)^{\frac{1}{4}} \]

Obukhov length (Statically Noneutral conditions)

\[ L = \left( \frac{-u^*^3}{k \left( \frac{g}{T_v} \frac{w'}{\theta'_s} \right)} \right) \]

\((k)\): Von Karman constant.

Convective mixed layer time scale:

\[ t_{ML}^* = \left( \frac{z_i}{w^*} \right) \]
Flying strategies

defined as a function of (consensus between):

Scientific goals and Capability of the aircraft

(autonomy, minimum and maximum heights, airspeed, payload/instruments,...)
NCAR C130 during DYCOMS-II
(DYNAMICS AND CHEMISTRY OF MARINE STRATOCUMULUS)
Studying the boundary layer vertical structure
DYCOMS-II
DYNAMICS AND CHEMISTRY OF MARINE STRATOCUMULUS

Stevens et al., BAMS, 84 (2003)
Fine-scale structure at stratocumulus cloud top

Figure 1. Schematic diagram showing the categories of segments referenced to cloud top that are used in the composited profiles.

Figure 2. Schematic diagram showing the slope of the cloud at the airplane penetration point $\alpha$ and the assumed slopes of the isotherms above cloud-top (parallel to cloud-top) and inside the cloud (horizontal).

Lenschow et al, 2000
RICO
Rain In Cumulus over the Ocean

Rauber, Stevens et al, 2007

RICO observational domain at three scales: Basin (top), regional (above), operational (left). Color plots show Dec-Jan climatology of rainrates from TRMM contoured, 10m wind from ERA40 (black streamlines on top and yellow arrows above), and SSTs in white contours from Reynolds et al., (2002).
HiCu
High Plains Cumulus

Damiani and Vali, 2007
Fig. 3. Flight patterns used for cumulus dynamics studies.

Damiani et al, 2008
CuPIDO

Cumulus, Photogrammetric, In situ and Doppler Observations

Fig. 4. Flight patterns used for BL dynamics and detrainment studies.

Damiani et al, 2008
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<tr>
<td>Antennas diameter</td>
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<td>Peak power</td>
<td>1.6 kW</td>
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<td>Pulse length</td>
<td>250 ns (33 m)</td>
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<td>Beam width</td>
<td>0.7°</td>
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<td>Repetition frequency</td>
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<td>Number of profiles per sec</td>
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**95 GHz WYOMING CLOUD RADAR**

![Image of radar data](image-url)
Growing cell

In-situ gust-probe data

Divergence associated with updraft top

Reflectivity dBZ

FSSP total conc. (# cm⁻³)

1d-c total conc. (# L⁻¹)

Air temperature (°C)

Liquid water content (g m⁻³)

Aug 26th, 2003
Lack of sensitivity
Higher Z at the sides of updraft. Coalescence/ Ice nucleation.

HiCu03 Aug26th VPDD 18:13:15-18:14:15
July 13th HBDD: final stages

HiCu03 Jul13th HBDD 21:03:30-21:04:12

along track distance [m]

1000 1500 2000 2500 3000 3500 4000

across track distance [m]

1000 1500 2000 2500 3000 3500 4000

10 m/s

Zh

4 0 -4 -8 -12 -16 -20 -24 -28

Jul 13th, 2003
Organized large scale horizontal dynamics

HiCu03 Jul12th 193510:193600 HBDD case

north-south distance [m]

west-east distance [m]
References - Textbooks


References - Articles


References - Articles


Stevens, B., 2006: Bulk boundary layer concepts for simplified models of tropical dynamics, *Theoretical and Computational Fluid Dyn.*, 20, 279–304


