Mesoscale Systems: weather associated with circulation systems of horizontal scales of 5 to 1,000 km

Typically associated with a fixed geographical feature, they are important for air pollution meteorology and dispersion

Divided into 2 categories

Thermal

1. Land-sea breeze
2. Monsoon circulations
3. Urban heat island induced circulations (city-country side circulation)
4. Mountain-valley winds

Mechanical (most important of air pollution dispersion is mountain-wake circulations)

1. Mountain wake vortices
2. Lee waves
Basic thermal circulation systems (eg. Land/sea breeze driven by differential surface heating)

Monsoon

Similar to land-sea breeze, except: Large sub-continental scale, flow changes seasonally, not diurnally (eg, E and SE Asia, winds blow one direction in summer and opposite direction in winter

Figure 3.10 Schematics of summer and winter monsoon circulations. From Miller and Thompson, 1970.
Urban Heat Island

Urban heat island intensity: \[ T_{u-r} = T_{urban} - T_{rural} \]
Max \[ T_{u-r} \] usually at night
Intensity of urban heat island depends on many factors
  - Size of city
  - Geographical location
  - Urban vegetation vs pavement
  - Time of day, season
  - Synoptic conditions
  - Max. usually clear calm nights
Mountain-Valley Winds

Figure 3.11 Schematics of (a) valley winds and (b) mountain winds associated circulations. Dashed lines represent constant pressure surfaces. Modified after Ahrens, 1994.

Mountain slope heats faster during day and cools faster at night
Dispersion in Mesoscale Systems

Mesoscale systems can have large effects on pollution transport and dispersion (pollutants released from source into the system).

![Diagram of Mesoscale Systems]

- Sea Breeze (daytime)
- Land Breeze (nighttime)
- Valley Breeze (daytime)
- Mountain Breeze (nighttime)
- Unstable (daytime)
- Stable (nighttime)

**Figure 3.12** Schematics of the effects of mesoscale systems on smoke stack plumes: (a) sea and land breezes; (b) mountain and valley winds; (c) topographically forced circulations. Modified after Pendergast, 1984.

e.g., thermal circulations
Most develop when large-scale gradient winds are weak. Then
• plumes follow local circulations
• pollutants can accumulate with time in closed thermal system
• often results in highest ground-level concentrations

At, other times it may be beneficial
black sloping lines dry adiabates (potential $T$ in °K); solid red lines, $q_s$
Dotted red lines, pseudoadiabates (equivalent potential $T$ in °K)
Example Problem: I.C.: $p = 900 \text{ mb}$, $T = 15^\circ \text{C}$, $q = 6.0 \text{ g/kg}$; $\Theta = 297 \text{K}$, $q_s = 12 \text{ g/kg}$

Find: RH = $6/12 = 50\%$, $T_{(dew \ point)} = 4^\circ \text{C}$

Raise parcel along constant pot. temp. to find $z$ of cloud base: $z(LCL) = 2.3 \text{ km asl}$

Raise parcel incloud to 650 mb, follow eq. pot. temp., $q_s = 4\text{ g/kg}$, so $6 - 4 = 2\text{ g/kg}$ $\text{H}_2\text{O}_v$ lost
Radiation Inversion
- Occur nightly
- Land surface cools by emitted IR (during day this is offset by UV heating)
- Ground cools layer of air above -> inversion
- Inversion strongest during long, calm, cloud free nights with dry air

Frontal Inversions
- Cold and warm fronts form along L pressure centers (esp. cyclones that predominate at 60°N)
- Warm air lifting along front produces inversion
- However, typically clouds and percip. along front lead to low pollution levels.

Marine Inversions
- Occur over coastal areas
- Cool marine air displaces warm air over land driven by land sea-breeze circulation
- This also contributes to LA smog problems
Large Scale Subsidence Inversions

- Occurs within a surface H pressure system
- Dry air descends, compresses, adiabatically warms
- Entire layer becomes more stable and often forms an inversion

- Persistent subsidence inversions lead to severe pollution episodes in subtropical cites: LA, Mexico City, Athens, (LA: Pacific high P produces large scale subsidence inversion 85-95% of the days)
- Often forms over near-surface air cooled by radiation
Small Scale Subsidence Inversions

Descending air compresses and warms, sits on top cool air
Examples:
  • Down flow from mountain slope produces inversion over valley
  • Stable air surrounding convective cloud formations
Microscale Systems and the PBL

- Scales ~ 10’s km
- PBL: region where friction dominates, above is geostrophic winds
- Most pollutants are released in PBL (except aircraft/rocket exhaust)
- On microscale geostrophic winds considered horizontal

- PBL evolves diurnally from diurnal heating/cooling
  Over oceans and snow/ice (polar regions in winter) little diurnal change

Figure 4.1 Schematic of the planetary boundary layer (PBL) as the lower part of the atmosphere.
**PBL**: region of sharp variations in winds due to air-surface interaction (height h)

**Mixed layer**: well mixed region (turbulent) often capped by T inversion (height $z_i$). Often h is assumed to equal $z_i$, but $z_i$ can be 5 to 25% lower than h

**Surface layer**: region of exchange of energy between surface and atm through strong heat transfer and turbulence (large gradients in T and wind speed)

Surface heating shortly after sunrise results in BL growth with time due to convective mixing and entrainment of air at BL top

Shortly after sunset surface cools, heat transfer from air to surface, cooling air forms a layer defined by a T inversion, called **surface inversion layer**.

Height of layer ($h_i$) grows, may reach h, but typically, $h_i < h$.

**Residual layer** contains previous days mixed layer and is disconnected from surface inversion layer.

---

**Figure 4.3** Diurnal variation of potential temperature profiles and the planetary boundary layer (PBL) height during (a) Day 33 and (b) the night of Days 33–34 of the Wangara Experiment. (c) Curve A is the PBL height during daytime and curve B is the surface inversion height at night. After Deardorff, 1978.
Daytime heating of surface (is a function of surface properties; $c_p$, $e$) -> heating of surface air -> unstable conditions -> air moves up and down following $\text{dry}$. Atm. $\text{dry}$ is modified. Convective layer develops between surface and inversion.

Depending on T of parcel at surface and inversion strength, air is trapped below inversion

- Inversion can be penetrated if
  - $T_{\text{surf.}}$ is high,
  - $\text{dry}$ can also lead to cloud formation above inversion.

Figure 4.4 Schematic of the diurnal variation of the planetary boundary layer height and structure in fair-weather conditions. Modified after Stull, 1988.
PBL Height Varies with location and season

Figure 3.14 Spatial variation of mean maximum mixing heights (m) over the United States for the months of (a) January and (b) July. From Holzworth, 1964.
PBL thickness has a large effect on pollutant concentrations

- Low PBL in morning + rush hour traffic - high pollution concentrations
- High well mixed PBL in late afternoon, rush hour not as evident (also pm rush hour generally spread over longer time.)
Typical Near-Surface Variations in Wind Speed and Direction

At surface, periodically observe a night time $O_3$ spike, thought to be due to nocturnal jet-induced downward mixing ($O_3$ higher above due to lack of titration).

Changes in wind speed and direction with height are less in the day than at night.

Mid day surface heating by solar radiation leads to convective mixing, PBL grows and wind speeds become uniform with height.

Wind shear in convective BL is only significant near surface.
Microscale systems and Dispersion

- Short range transport and diffusion determined by PBL distribution of mean winds and turbulence.
- Mean winds: effect average speed and direction pollutants move with height.
- Turbulence: rate of horiz. & vert. spread of pollutants (plume dimensions increase with distance (time) from source).
- Plumes eventually mixed throughout PBL, then at larger distances dispersed by successively large scales of motion (synoptic systems etc) -> becomes regional pollution.
PBL Modeling

Need f(z): mean wind, speed/direction, and turbulence

Simple models
- Mean wind speed and direction at pollutant release ht.
- Estimate of PBL ht.
- Some indirect measure of turb. (e.g., atm stability)

Applied Dispersion Models
- mean winds, turb., mixing ht: parameterized using semi-empirical and theoretical relations for PBL

Numerical Dispersion Models:
- numerically compute wind and turb. fields
- only these models can account for inhomogeneous mean wind and turb. over small scale surface inhomogeneities (these can be important, e.g., pollutant released in a recirculation zone of building can lead to high concentrations)
- obstacles lead to increased ground-level pollution concentrations in wakes
- estimate by terrain amplification factor
  \[ = \frac{\text{max. g.l.c. in wake}}{\text{without wake}} \]
Richardson Number and the formation and maintenance of turbulence

Figure 4.6 Measured wind, potential temperature, and specific humidity profiles in the planetary boundary layer. (a) convective conditions on Day 33 of the Wangara Experiment. (b) very stable conditions on the night of Day 34 of the Wangara Experiment. Richardson number profile is also shown. From Deardorff, 1978.
Turbulence:

Figure 4.7 Measured time series of velocity, temperature, and absolute humidity fluctuations at a suburban site in Vancouver, Canada, during moderately unstable conditions. From Roth, 1990.

Sampling ht: 27.4 m, moderately unstable conditions
Turbulent fluctuations

Under strong winds, near-neutral stability:
  • Horiz. and vert. velocity, temp, humidity fluctuations tend to be symmetrical about mean.

Unstable convective conditions:
  • Strong asymmetry between positive and negative fluctuations.

In typ. daytime unstable surface layer magnitude of vertical velocities fluctuations much larger than mean vertical velocity, horiz. vel. fluctuations are same order of mag. or less than mean wind speed, mag. of T fluctuations is less than 1% of mean absolute temperature.

The relative magnitude of turbulent fluctuations generally decreases with increasing PBL stability.
Surface roughness ($z_0$)

<table>
<thead>
<tr>
<th>Surface</th>
<th>$z_0$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very smooth (ice, mud flats)</td>
<td>$10^{-5}$</td>
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<tr>
<td>Snow</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>Smooth sea</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>Level desert</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>Lawn</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>Uncut grass</td>
<td>0.05</td>
</tr>
<tr>
<td>Fully grown root crops</td>
<td>0.1</td>
</tr>
<tr>
<td>Tree covered</td>
<td>1</td>
</tr>
<tr>
<td>Low-density residential</td>
<td>2</td>
</tr>
<tr>
<td>Central business district</td>
<td>5–10</td>
</tr>
</tbody>
</table>

Source: McRae et al. (1982).
Stack Plumes

Figure 3.16 Schematic depictions of instantaneous plume patterns in the vertical and the corresponding wind speed and temperature profiles (modified after Slade, 1968).

Fig. 6.13. Commonly observed behaviour of factory smoke plumes. Views shown are at right angles to the wind direction and the plumes are also given in cross section. (a) Coning. This occurs under near-neutral conditions, which lead to approximately equal dispersion in both the horizontal (cross-wind) and vertical directions. (b) Lofting. This occurs when emission is just above an inversion layer. (c) Looping. This occurs under unstable conditions. (d) Fanning. This occurs under very stable conditions (i.e. an inversion), which leads to much horizontal dispersion, but little vertical spread. (e) Fumigation. This is caused by emission just below an inversion layer.
From Seinfeld and Pandis, pg 925, Gaussian plume Equations

| Gaussian plume formula | Total reflection at $z = 0$
|------------------------|-----------------------------------|
| $c(x, y, z) = \frac{q}{2\pi \bar{u} \sigma_x \sigma_z} \exp \left( -\frac{y^2}{2\sigma_y^2} \right) \left[ \exp \left( -\frac{(z-h)^2}{2\sigma_z^2} \right) + \exp \left( -\frac{(z+h)^2}{2\sigma_z^2} \right) \right]$ | $\mathbf{\tilde{u}} = (\bar{u}, 0, 0)$
| | $S = q \delta(x) \delta(y) \delta(z - h)$
| | Slender plume approximation
| | $0 \leq z \leq \infty$ |

| Gaussian plume formula | Total absorption at $z = 0$
|------------------------|-----------------------------------|
| $c(x, y, z) = \frac{q}{2\pi \bar{u} \sigma_x \sigma_z} \exp \left( -\frac{y^2}{2\sigma_y^2} \right) \left[ \exp \left( -\frac{(z-h)^2}{2\sigma_z^2} \right) - \exp \left( -\frac{(z+h)^2}{2\sigma_z^2} \right) \right]$ | $\mathbf{\tilde{u}} = (\bar{u}, 0, 0)$
| | $S = q \delta(x) \delta(y) \delta(z - h)$
| | Slender plume approximation
| | $0 \leq z \leq \infty$ |

| Gaussian plume formula | Total reflection at $z = 0$
|------------------------|-----------------------------------|
| $c(x, y, z) = \frac{2q}{\sqrt{2\pi \bar{u} \sigma_y H}} \left\{ \frac{1}{2} + \sum_{n=1}^{\infty} \cos \left( \frac{n\pi z}{H} \right) \cos \left( \frac{n\pi h}{H} \right) \right\} \times \exp \left[ -\left( \frac{n\pi}{H} \right)^2 \frac{\sigma_y^2}{2} \right] \exp \left( -\frac{y^2}{2\sigma_y^2} \right)$ | $\mathbf{\tilde{u}} = (\bar{u}, 0, 0)$
| | $S = q \delta(x) \delta(y) \delta(z - h)$
| | $0 \leq z \leq H$
| H: inversion height |
From Seinfeld and Pandis, *Air Atmospheric Chemistry and Physics*

<table>
<thead>
<tr>
<th>Reference</th>
<th>Atmospheric Stability</th>
<th>$a$</th>
<th>$b$</th>
<th>$E$</th>
<th>Conditions</th>
</tr>
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<tbody>
<tr>
<td><strong>Plumes Dominated by Buoyancy Forces</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASME (1973)</td>
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<td>0</td>
<td>$7.4 \left( \frac{F h_e^2}{S_1} \right)^{1/3}$</td>
<td>$F &lt; 55, \ x &lt; 49 F^{5/8}$</td>
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<td>$29 \left( \frac{F}{S_1} \right)^{1/3}$</td>
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<td>Briggs (1969, 1971, 1974)</td>
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<td>$F \geq 55, \ x &lt; 119 F^{2/5}$</td>
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<tr>
<td></td>
<td></td>
<td>1</td>
<td>0</td>
<td>$21.4 F^{3/4}$</td>
<td>$F \geq 55, x \geq F^{3/8}$</td>
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<td></td>
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<td>$\frac{1}{3}$</td>
<td>$1.6 F^{1/3}$</td>
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<tr>
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<td>1</td>
<td>0</td>
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<td>Stable $^b,c$</td>
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<td>0</td>
<td>$5 F^{1/4} S_2^{-3/8}$</td>
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<tr>
<td></td>
<td></td>
<td>$\frac{1}{3}$</td>
<td>$\frac{1}{2}$</td>
<td>$1.6 F^{1/3}$</td>
<td></td>
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<tr>
<td><strong>Plumes Dominated by Momentum Forces</strong></td>
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<tr>
<td>ASME (1973)</td>
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<td>0</td>
<td>$d V_e^{1.4}$</td>
<td>$V_e &gt; 10 \text{ m s}^{-1}$ \ $V_e &gt; \bar{u}$ \ $\Delta T &lt; 50 \text{ K}$</td>
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<tr>
<td>Briggs (1969)</td>
<td>Neutral $^d$</td>
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<td>$\frac{1}{3}$</td>
<td>$1.44 (d V_e)^{2/3}$</td>
<td>$V_e / \bar{u} \geq 4$</td>
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<tr>
<td></td>
<td></td>
<td>1</td>
<td>0</td>
<td>$3 d V_e$</td>
<td>$V_e / \bar{u} \geq 4$</td>
</tr>
</tbody>
</table>

Nomenclature for Table 18.3:
- $d =$ stack diameter, m
- $F =$ buoyancy flux parameter, $g d^2 V_e (T_e - T_o) / 4 T_e$, m$^4$ s$^{-3}$
- $g =$ acceleration of gravity, 9.807 m s$^{-2}$
- $p =$ atmospheric pressure, kPa
- $p_0 =$ 101.3 kPa
- $S_1 =(g \partial V_e / \partial T_e) (p / p_0)^{0.29}$ s$^{-2}$
- $S_2 =(g \partial V_e / \partial T_e) / T_e$, s$^{-2}$
- $T_e =$ ambient temperature at stack height, K
- $T_o =$ stack exit temperature at stack height, K
- $\Delta T =$ $T_e - T_o$
- $V_e =$ stack exit velocity, m s$^{-1}$

$^a$For further information we refer the reader to Hanna et al. (1982).

$^b$The appropriate field data are not available to estimate $s_1$ and $s_2$, i.e. $s_1 = s_2$ can be used.

$^c$Of these formulas for stable conditions, use the one that predicts the least plume rise.

$^d$Of the two formulas for neutral conditions, use the one that predicts the least plume rise.
FIGURE 18.1 Correlations for $\sigma_y$ based on the Pasquill stability classes A to F (Gifford, 1961). These are the so-called Pasquill–Gifford curves.

FIGURE 18.2 Correlations for $\sigma_z$ based on the Pasquill stability classes A to F (Gifford, 1961). These are the so-called Pasquill–Gifford curves.
## TABLE 18.2 Coefficients in Gaussian Plume Dispersion Parameter Correlations\(^a\)

\[
\begin{align*}
\sigma_y(x) &= R_y x^{r_y} \\
\sigma_z(x) &= R_z x^{r_z} \\
\sigma_y(x) &= \exp[I_y + J_y \ln x + K_y (\ln x)^2] \\
\sigma_z(x) &= \exp[I_z + J_z \ln x + K_z (\ln x)^2]
\end{align*}
\]

<table>
<thead>
<tr>
<th>Source</th>
<th>Averaging Time (min)</th>
<th>Coefficient</th>
<th>(A)</th>
<th>(B)</th>
<th>(C)</th>
<th>(D)</th>
<th>(E)</th>
<th>(F)</th>
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<tr>
<td>Pasquill–Gifford (Turner, 1969; Martin, 1976)</td>
<td>10</td>
<td>(R_y)</td>
<td>0.443</td>
<td>0.324</td>
<td>0.216</td>
<td>0.141</td>
<td>0.105</td>
<td>0.071</td>
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<tr>
<td></td>
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<td>(r_y)</td>
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<td>0.894</td>
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<td>0.894</td>
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<td>(R_y)</td>
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<td></td>
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<td>0.91</td>
<td>0.86</td>
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<td>Klug (1969)</td>
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<tr>
<td></td>
<td></td>
<td>(J_y)</td>
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<td></td>
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<tr>
<td></td>
<td></td>
<td>(K_y)</td>
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<td>-0.0087</td>
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<td>-0.0316</td>
<td>-0.0450</td>
<td>-0.0540</td>
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\(^a\) Application restricted to downwind distances not exceeding 10 km (Hanna et al., 1982).
Table 4.2 Meteorological Conditions Defining Pasquill’s Stability/Turbulence Types*

<table>
<thead>
<tr>
<th>Surface (10 m) Wind Speed (m s⁻¹)</th>
<th>Daytime</th>
<th>Nighttime</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strong</td>
<td>Moderate</td>
</tr>
<tr>
<td>&lt;2</td>
<td>A</td>
<td>A-B</td>
</tr>
<tr>
<td>2–3</td>
<td>A-B</td>
<td>B</td>
</tr>
<tr>
<td>3–5</td>
<td>B</td>
<td>B-C</td>
</tr>
<tr>
<td>5–6</td>
<td>C</td>
<td>C-D</td>
</tr>
<tr>
<td>&gt;6</td>
<td>C</td>
<td>D</td>
</tr>
</tbody>
</table>

*A, extremely unstable; B, moderately unstable; C, slightly unstable; D, neutral (applicable to overcast conditions day or night); E, slightly stable; F, moderately stable.

Table 4.3 Approximate Correspondence Between Pasquill’s Stability Classes and Turbulence Parameters $\sigma_\theta$ and $\sigma_\phi$

<table>
<thead>
<tr>
<th>Pasquill’s Stability Class</th>
<th>$\sigma_\theta$ (deg.)</th>
<th>$\sigma_\phi$ (deg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>≥22.5</td>
<td>≥11.5</td>
</tr>
<tr>
<td>B</td>
<td>17.5–22.5</td>
<td>10.0–11.5</td>
</tr>
<tr>
<td>C</td>
<td>12.5–17.5</td>
<td>7.8–10.0</td>
</tr>
<tr>
<td>D</td>
<td>7.5–12.5</td>
<td>5.0–7.8</td>
</tr>
<tr>
<td>E</td>
<td>3.8–7.5</td>
<td>2.4–5.0</td>
</tr>
<tr>
<td>F</td>
<td>&lt;3.8</td>
<td>&lt;2.4</td>
</tr>
</tbody>
</table>

*Source: Irwin, 1980.*