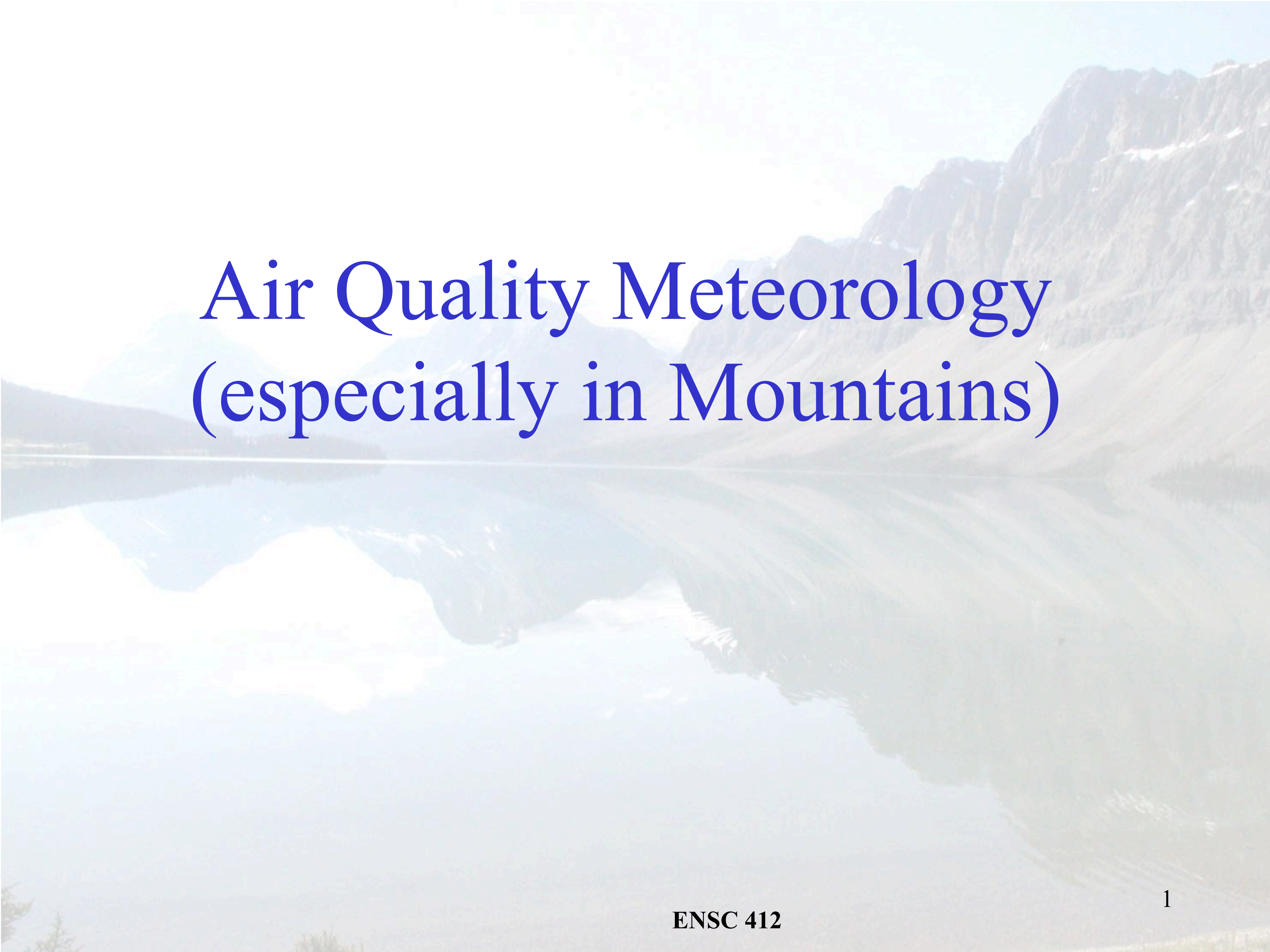


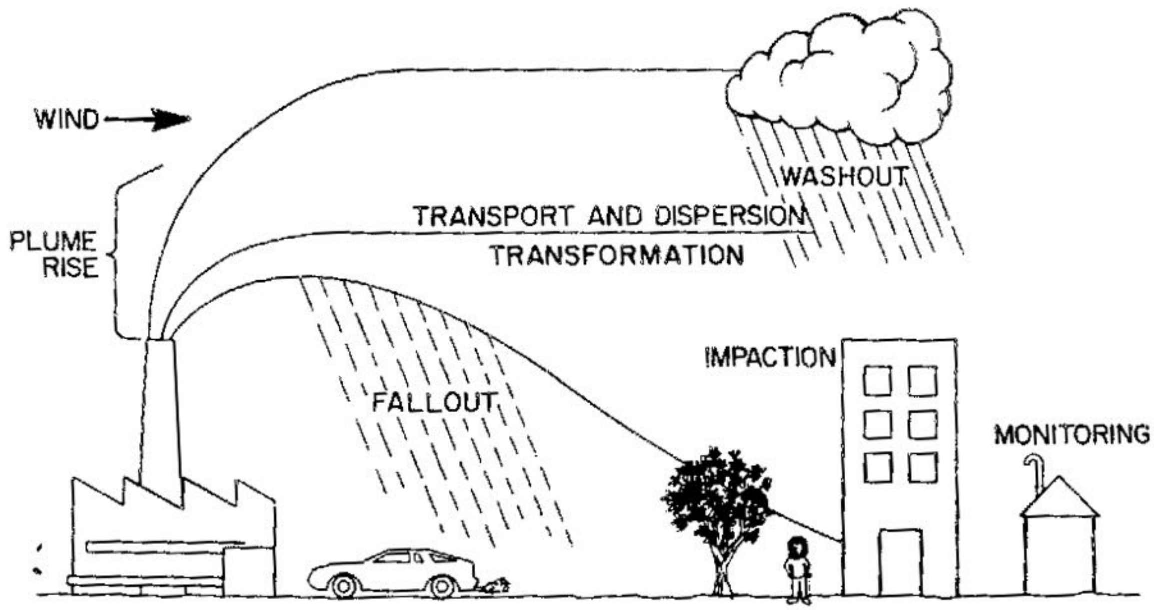
Air Quality Meteorology (especially in Mountains)

Readings for this week

- Text Chapters 17, 18, 21
- Ainslie, B. and D.G. Steyn, 2007: Spatiotemporal Trends in Episodic Ozone Pollution in the Lower Fraser Valley, British Columbia, in Relation to Mesoscale Atmospheric Circulation Patterns and Emissions. J. Appl. Meteor. Climatol. 46, 1631-1644

1. Air Quality Meteorology

- Atmosphere is the link between source and receptor
- Atmosphere transforms and removes as well as transports and disperses pollutants → movement and dilution
- AQ is an issue when dispersion is poor → light wind, high stability, anticyclonic
- What are the important characteristics of **sources, atmosphere, receptors** that affect pollutant concentration?



SOURCE	ATMOSPHERE	RECEPTOR
LOCATION	TRANSPORT WIND DIRECTION LOCAL CIRCULATIONS	LOCATION
CONFIGURATION	DILUTION WIND SPEED	MONITORING
EMISSIONS TIME AND DURATION	DISPERSION TURBULENCE	SENSITIVITY PLANTS (WEATHER RELATED) HUMANS
CHARACTERISTICS HEIGHT VOLUME FLOW TEMPERATURE	TRANSFORMATION CHEMICAL PHYSICAL	REMOVAL FALLOUT DEPOSITION WASHOUT IMPACTION

Fig. 18-1. The atmosphere's role in air pollution.

Atmospheric Controls

- Largely controls vertical movements of pollutants.
- Unstable → large eddies → enhanced vertical diffusion.
- Stable → decreased turbulence and diffusion.
- Presence of inversions is very important for vertical diffusion.

- There are several types of inversions: 1) surface-based, nocturnal; 2) subsidence warming; and 3) advective (such as associated with warm fronts, advecting warm air over a cold surface).
- Advective inversions are not as important for air pollution as the air is usually in movement.

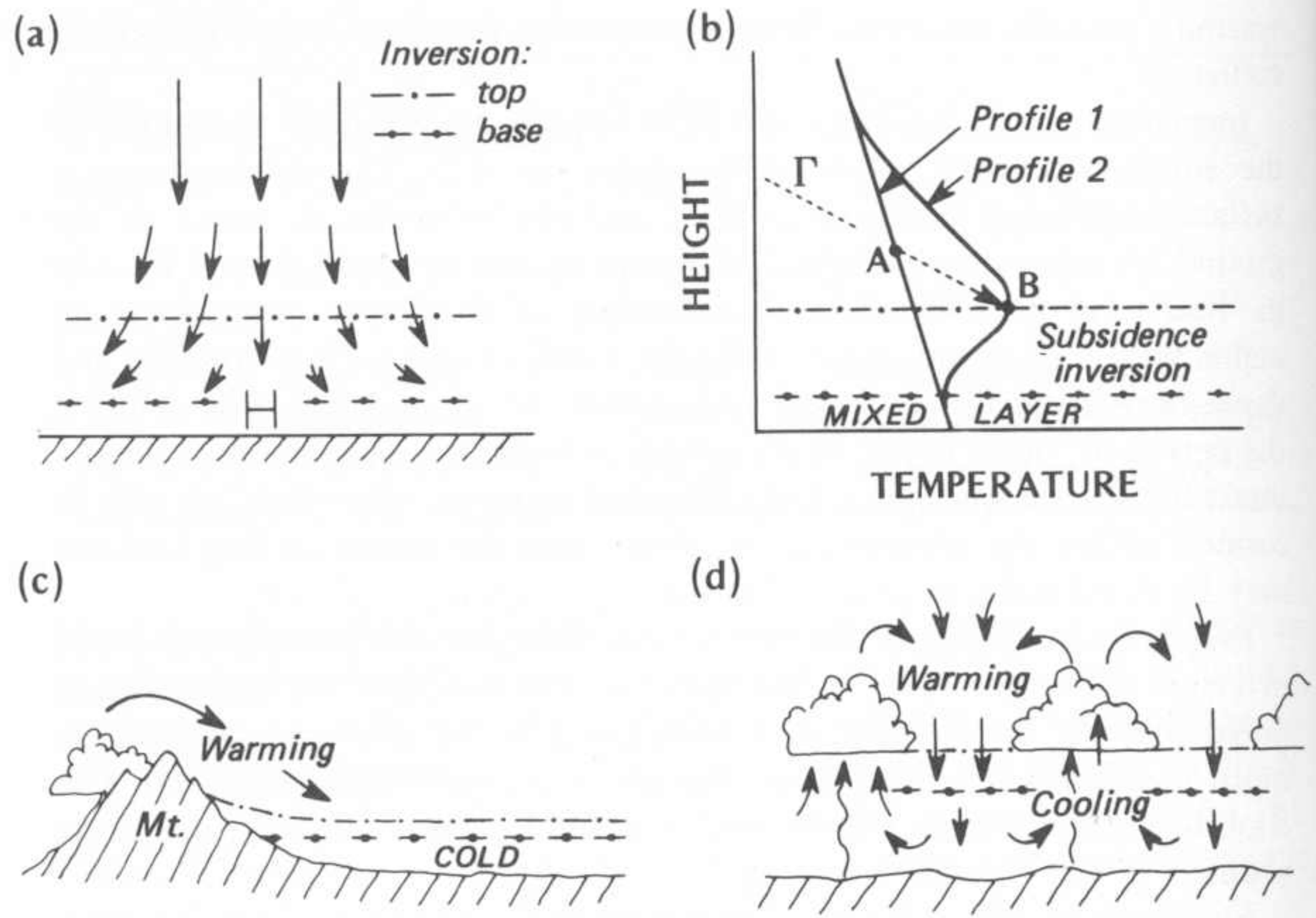


Figure 9.2 Inversions formed by adiabatic warming due to subsidence. (a) and (b) in an anticyclone, (c) in the lee of mountains, and (d) in convection cells between clouds.

Oke (1987)

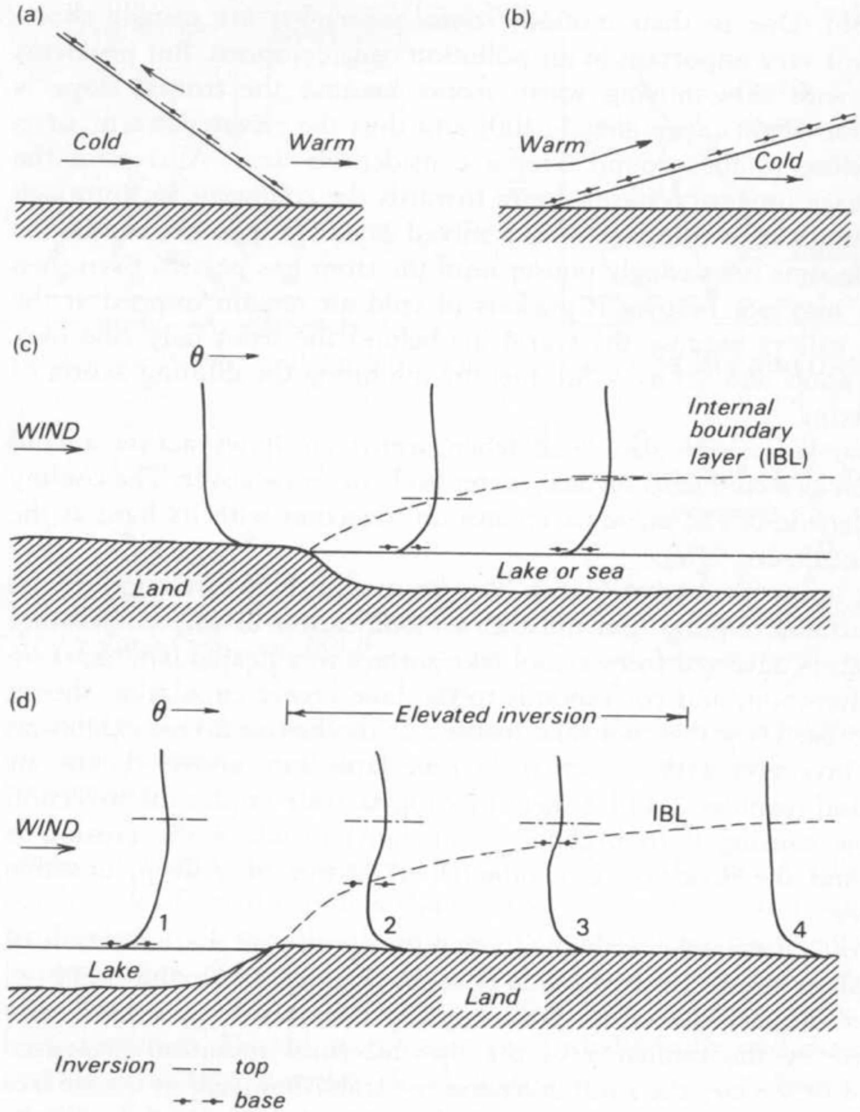


Figure 9.3 Inversions due to advection. A frontal inversion caused by (a) cold air wedging under warmer air (cold front), and (b) warm air over-riding colder air (warm front). (c) The modification of an unstable temperature profile to give a surface-based inversion over a cool water body. (d) Elevated inversion due to the advection of stable lake air across the shoreline to a warmer land area on a spring afternoon. Vertical temperature profiles are plotted in potential temperature, θ (p. 53).

Oke (1987)

Effect of wind

- Wind diffuses pollutants by stretching them along the wind direction.
- Wind speed also enhances turbulence, and thus vertical and horizontal diffusion.
- Variations in wind direction are also important as they lead to sinuous plumes

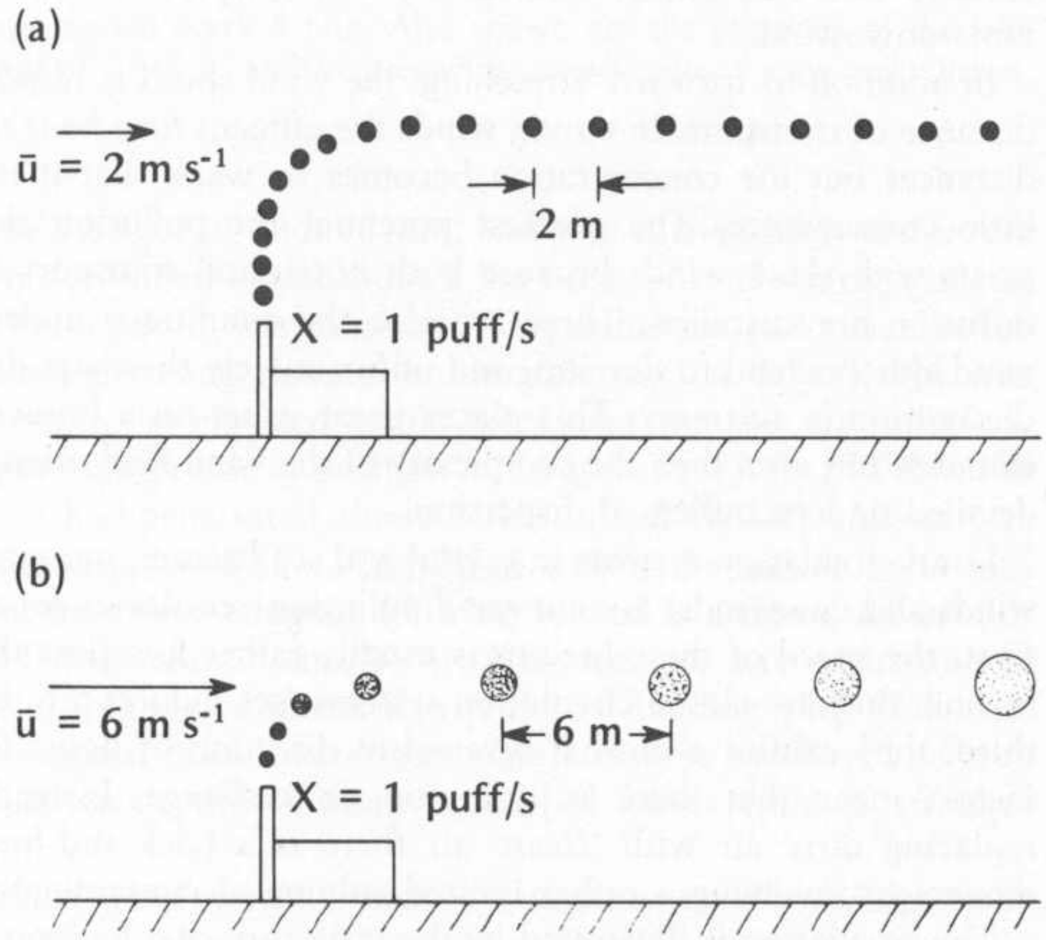


Figure 9.4 The effect of wind speed upon pollution concentration. In both cases the rate of emission (X) is 1 puff per second, but in (a) the wind speed ($\bar{u}$) is 2 m s^{-1}, whereas in (b) it is 6 m s^{-1}.

Oke (1987)

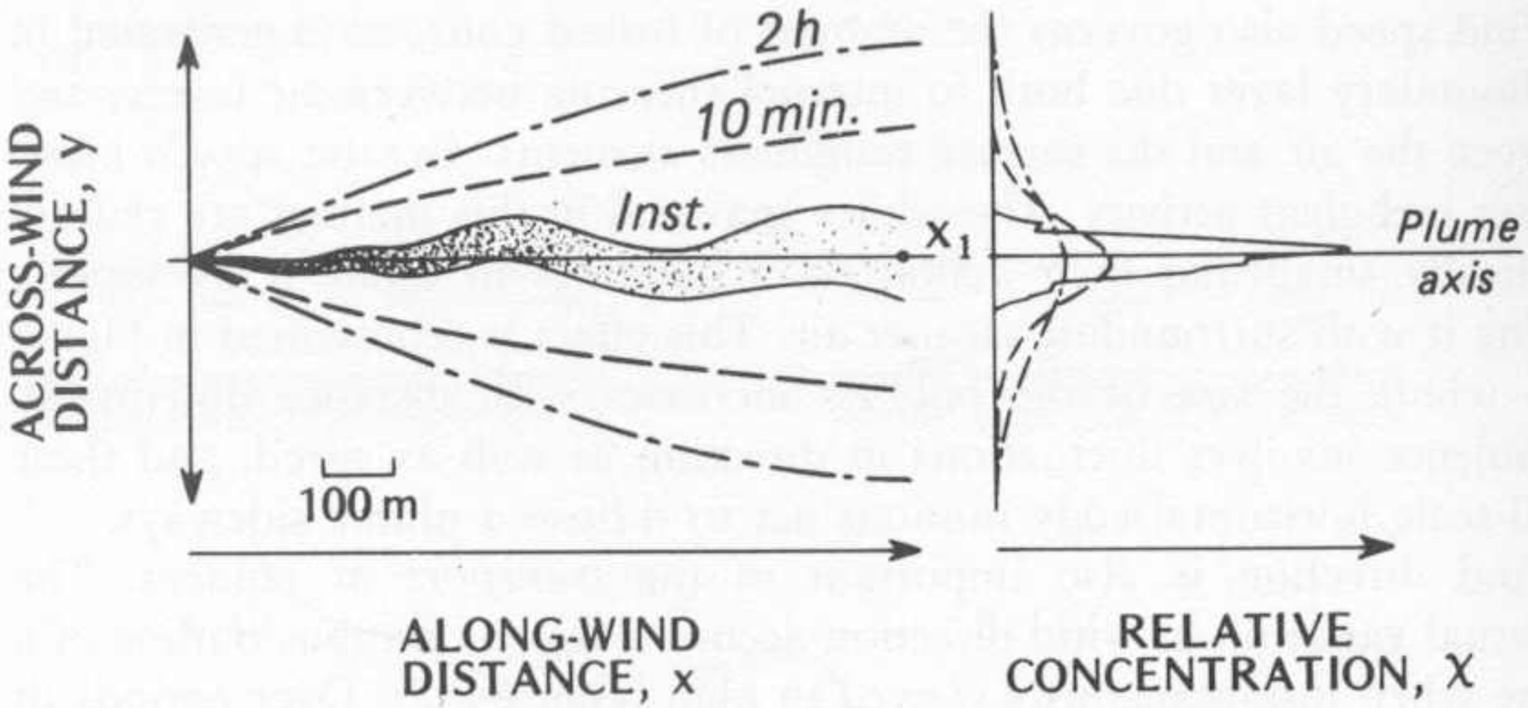


Figure 9.5 Plan view of the approximate outlines of a smoke plume observed instantaneously, and averaged over periods of 10 min and 2 h. At the right are the corresponding cross-plume concentration distributions at the distance x_1 downwind (after U.S. AEC, 1968).

Oke (1987)

- The greatest potential for pollution is in low wind situations because horizontal transport and turbulent diffusion are both curtailed.
- Local circulations (land/sea breezes etc.) are not good pollution ventilators because they are associated with low wind speeds, they are closed systems, and there usually is a diurnal reversal → pollution comes back.

- Depending on local meteorology, pollution may recirculate, thus increasing concentration over a period of days.
- Topography and/or climate conspires to limit ventilation (e.g., Vancouver, Prince George, Los Angeles, or Mexico City).

UNBC

Graduate Teaching Excellence Award

College of Science and Management

MCPMS and NRES Graduate Programs

The College of Science and Management offers one teaching award per year for graduate teaching assistants. Any graduate student who has taught in the College during the Fall 2016 and/or Winter 2017 semesters may be nominated.

Each nomination must be signed by **five** undergraduate students, and should be **accompanied by a letter** addressing the award criteria. Nomination forms are available from the Office of the Dean of CSAM or may be accessed from the UNBC CSAM website
http://www.unbc.ca/csam/forms.html

The award criteria are:

- exceptional teaching
- clear and effective instruction and assistance to students
- motivation and inspiration of students to learn

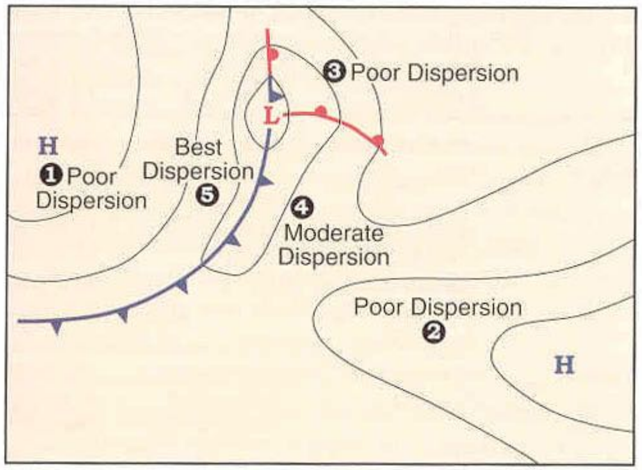
Nominations must be received in the Office of the Dean of CSAM (Admin Building 1047) by Friday, April 7, 2017 at 4pm
Questions? Contact teresa.bell@unbc.ca

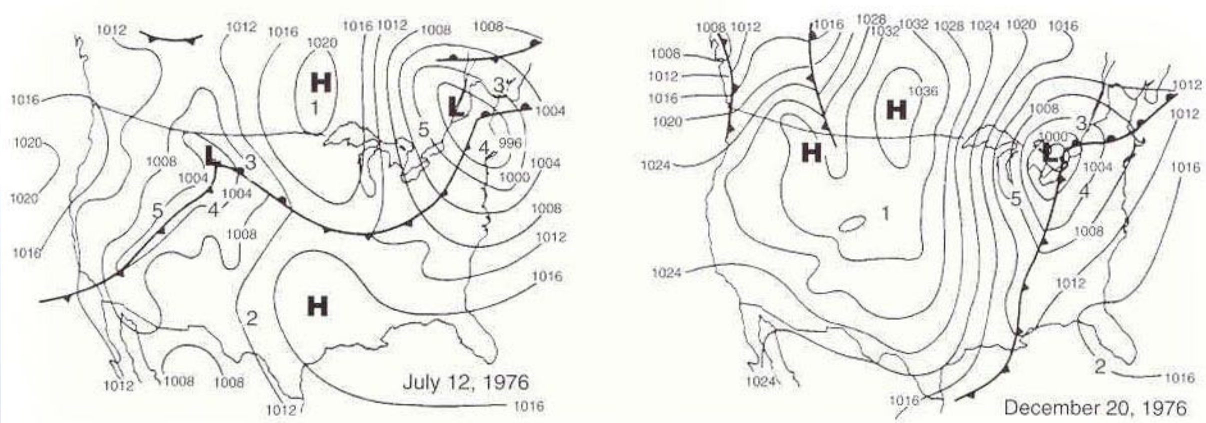
UNBC UNIVERSITY OF NORTHERN BRITISH COLUMBIA 3333 University Way • Prince George, BC • Canada • V2N 4Z9

Ventilation

- Related to wind speed and atmospheric stability (mixing height or boundary layer depth)
- What are wind speed effects?
- Weather conditions have a big impact on ventilation

Synoptic conditions and poor AQ





Cyclonic conditions

- Areas of Low pressure are generally
  - fast moving,
  - associated with strong winds and
  - upward motion, clouds and precipitation

→ all result in low pollutant concentrations

Anticyclonic conditions

- High pressure areas have the opposite conditions:
  - Often slow moving and stagnant
  - Associated with weak pressure gradients and light winds
  - Downward motion – clear skies and no precip
  - Formation of a subsidence inversion that stabilizes the atmosphere and limits vertical mixing

  → Conditions that lead to stagnation and high pollutant concentrations

AQ Issues during subsidence inversion conditions

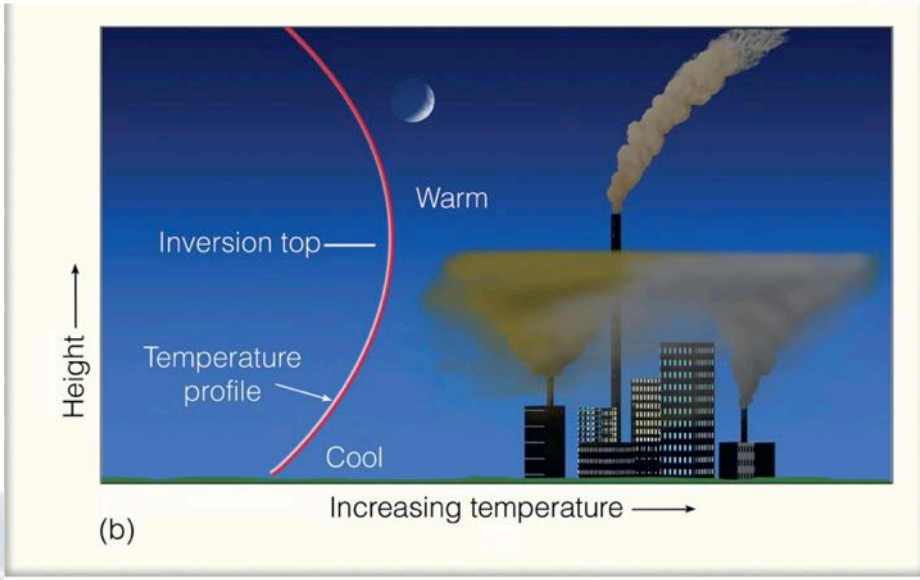


FIGURE 18.11 (a) During the afternoon, when the atmosphere is most unstable, pollutants rise, mix, and disperse downwind. (b) At night, when a radiation inversion exists, pollutants from the shorter stacks are trapped within the inversion, whereas pollutants from the taller stack, above the inversion, are able to rise and disperse downwind.

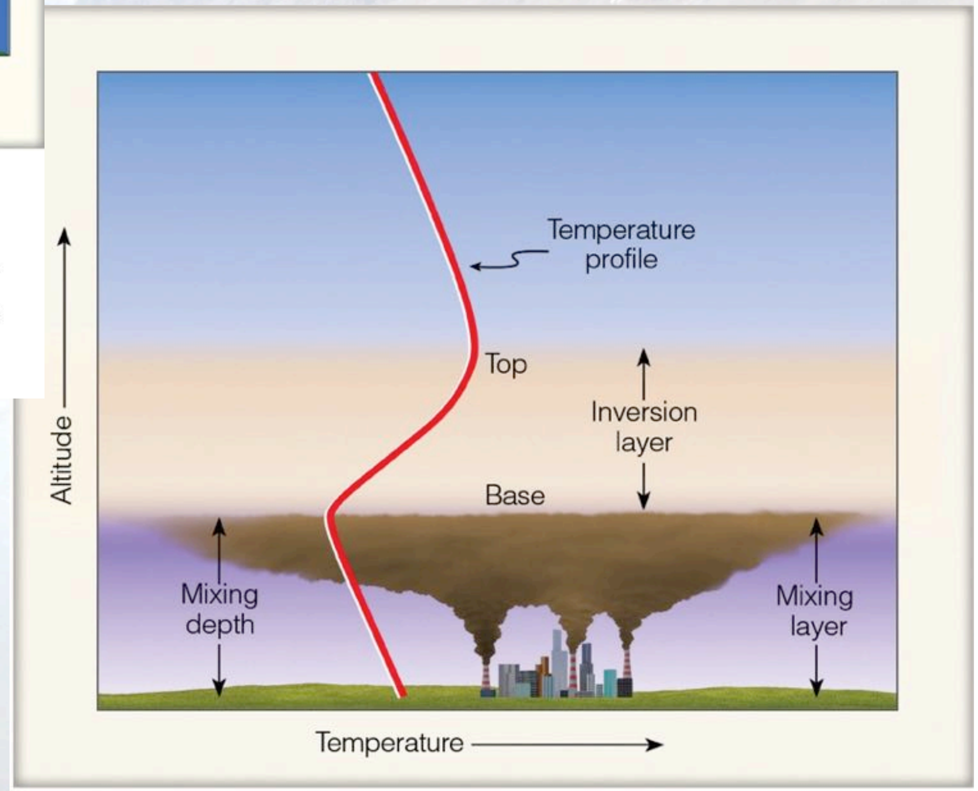
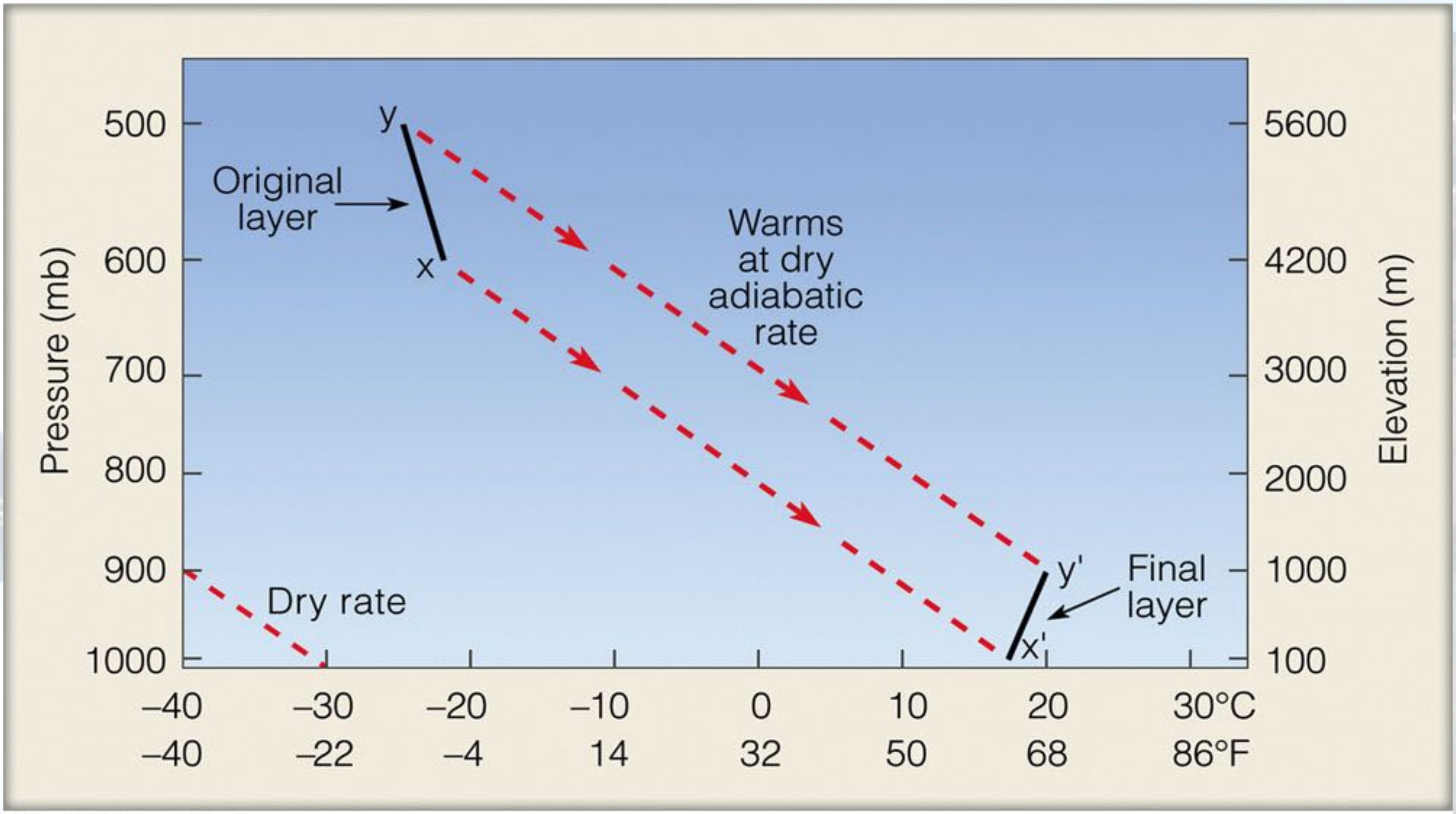


FIGURE 18.12 The inversion layer acts as a lid on the pollutants below. If the inversion lowers, the mixing depth decreases, and the pollutants are concentrated within a smaller volume.

Ahrens, Jackson, Jackson (2016)

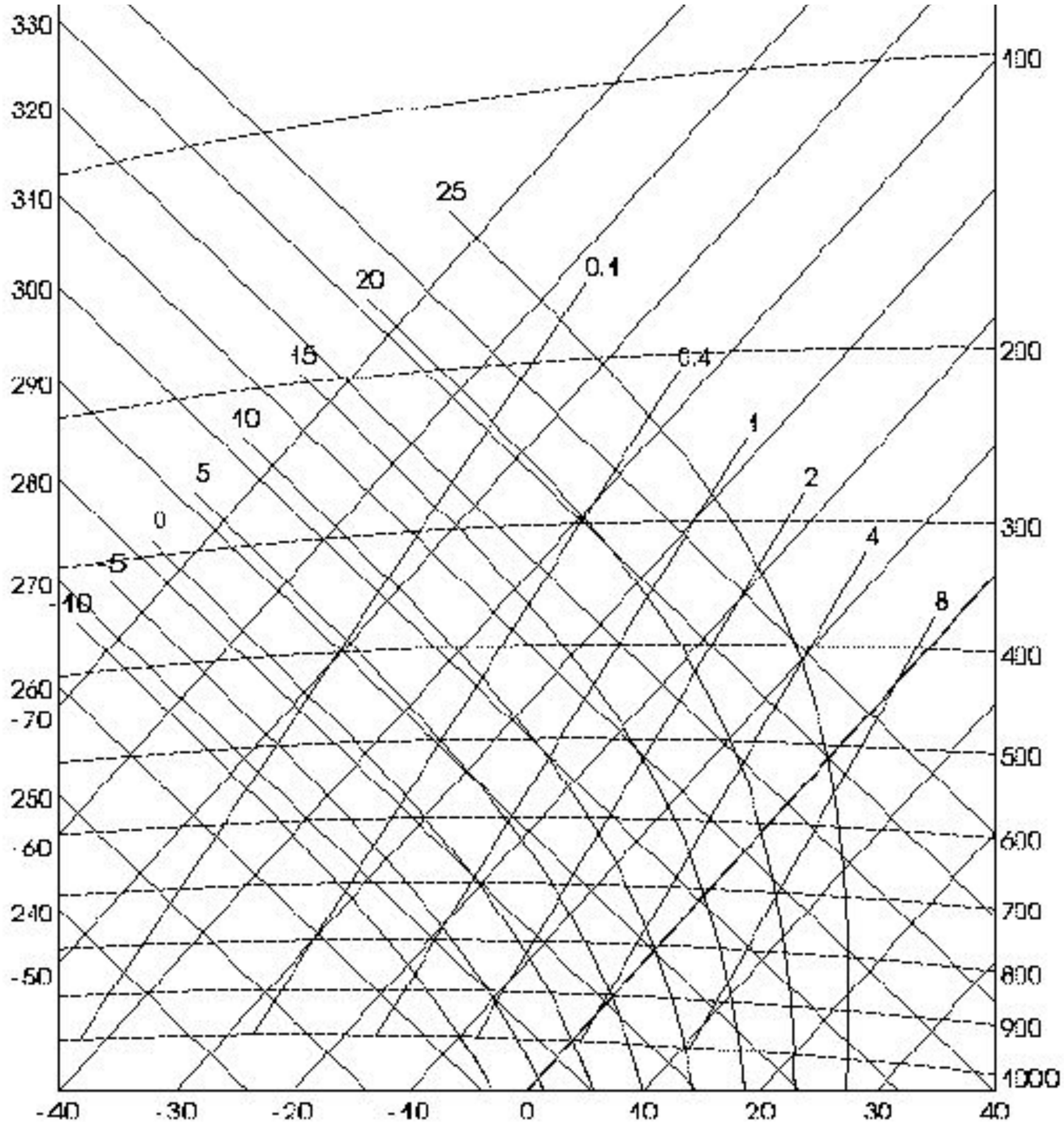


© Brooks/Cole, Cengage Learning

Subsidence inversion due to adiabatic warming of downward moving air (usually in an area of High Pressure)

Mixing heights

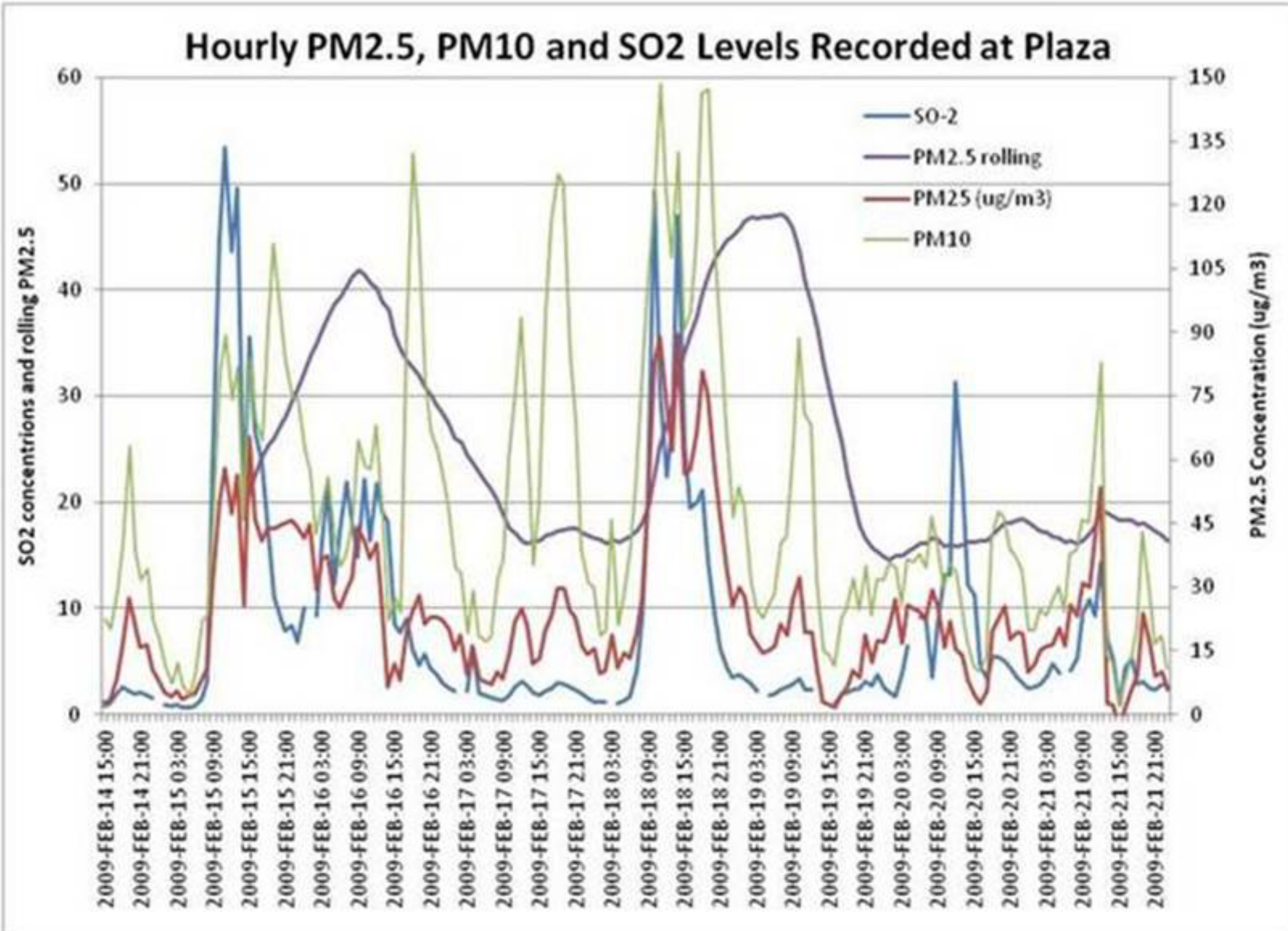
- Are usually estimated from atmospheric soundings…



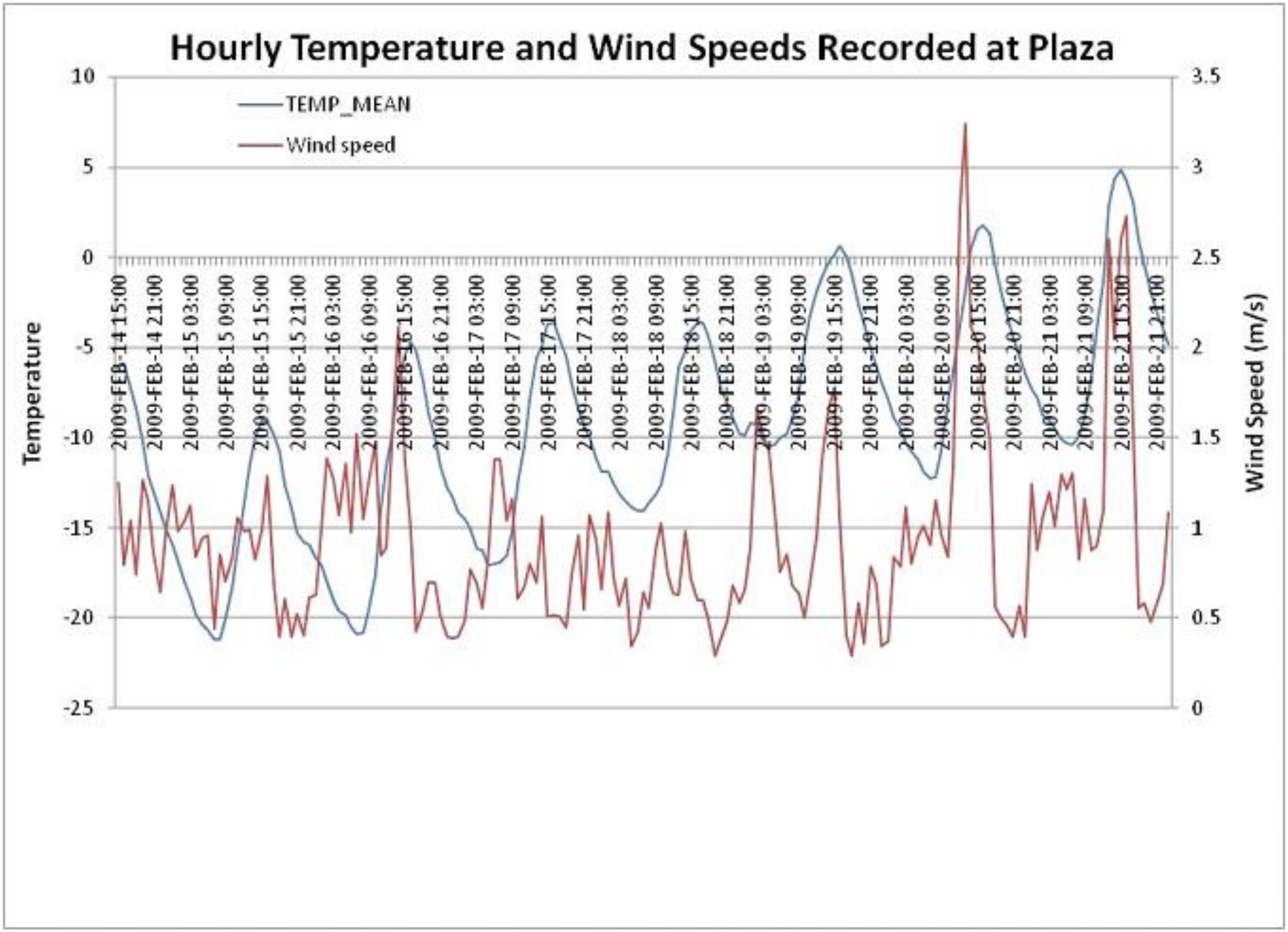
Mixed layer is usually a neutral layer surmounted by an inversion or stable layer

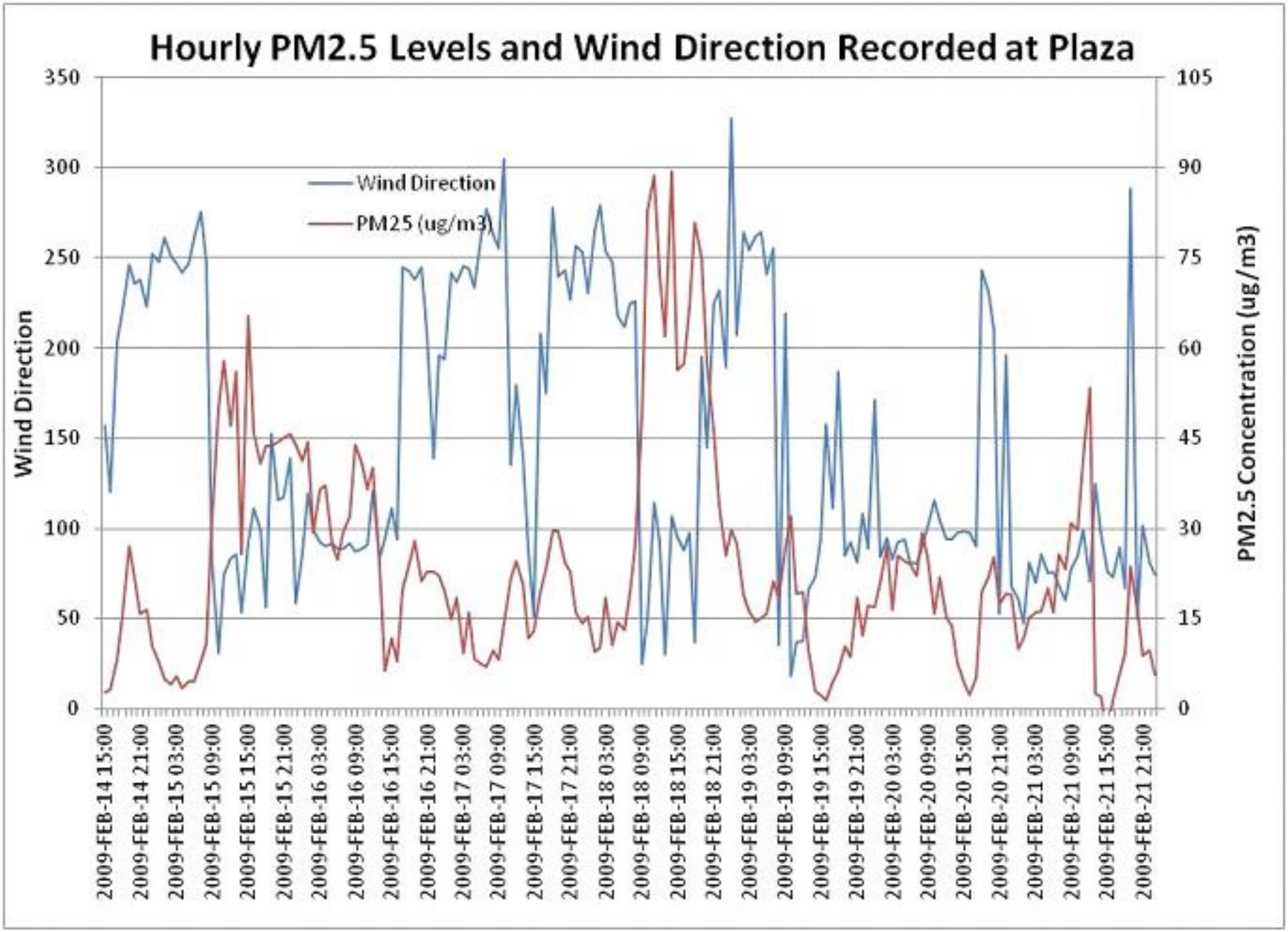
Stagnation

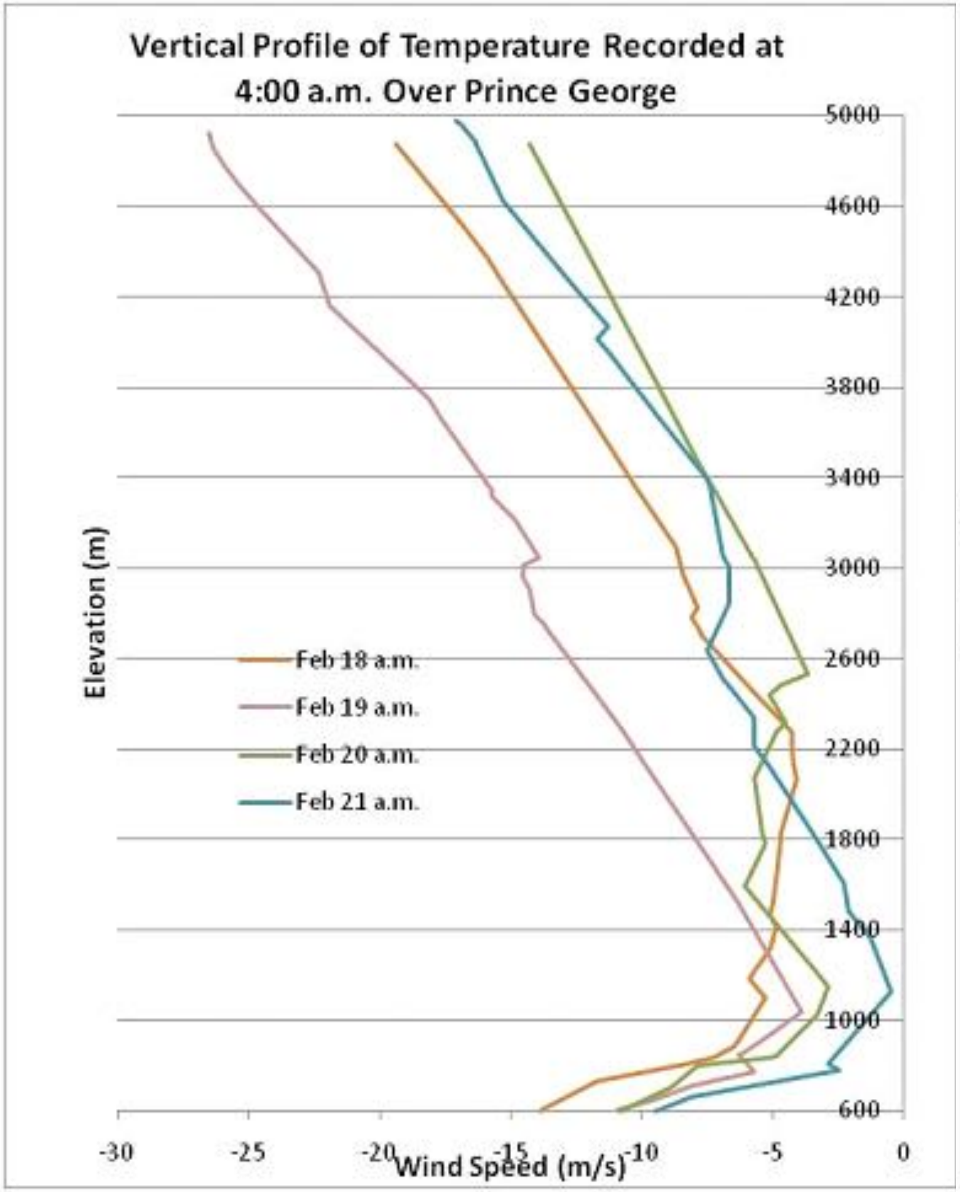
- Conditions are the cause of most AQ episodes
  - Meuse Valley, Belguim Dec 1-5 1930 63 Dead
  - Donora, Pennsylvania, Oct 25-31 1948 20 Dead
  - London, England, Dec 5-9 1952 several thousand Dead
  - Prince George Feb 16-20 2009! ?? Dead?

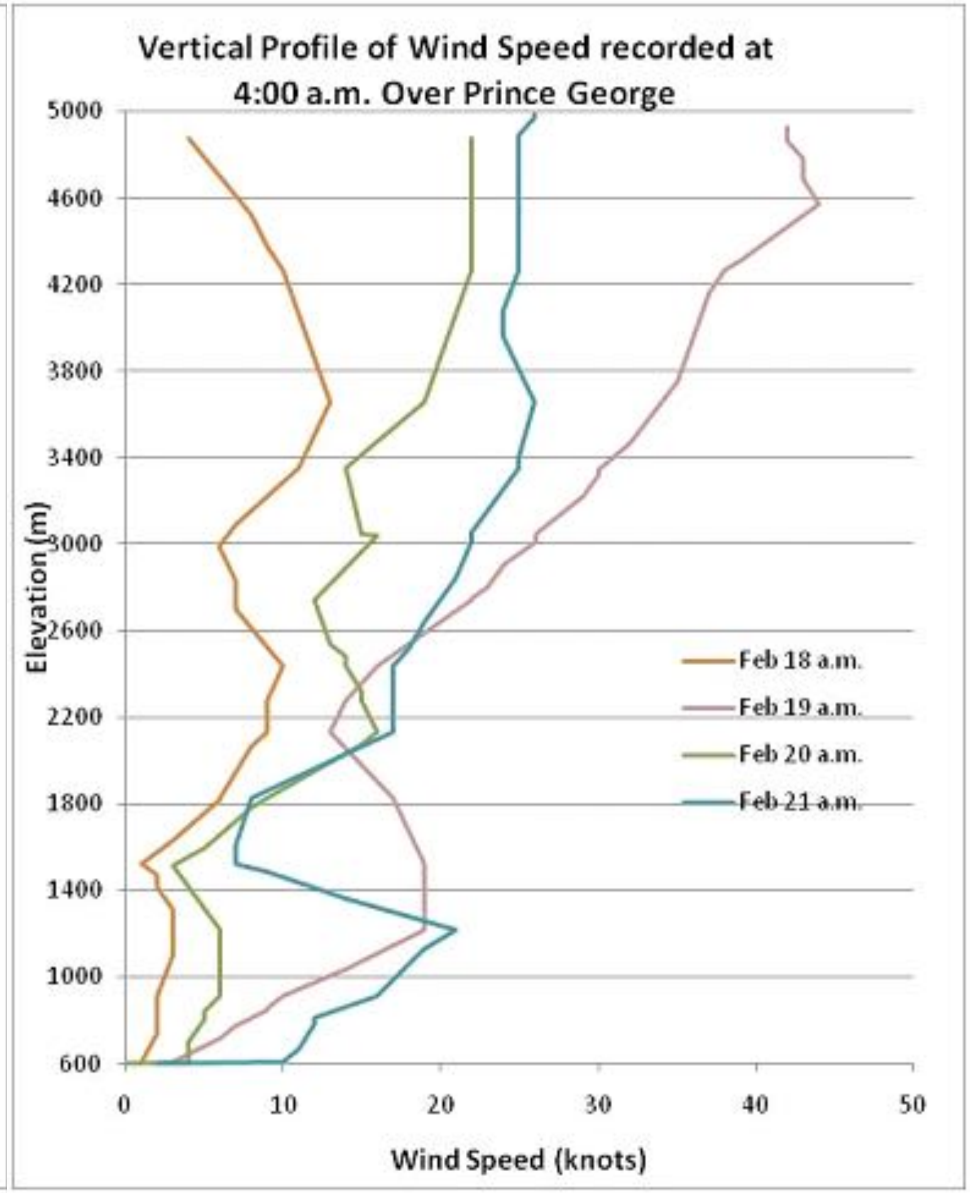


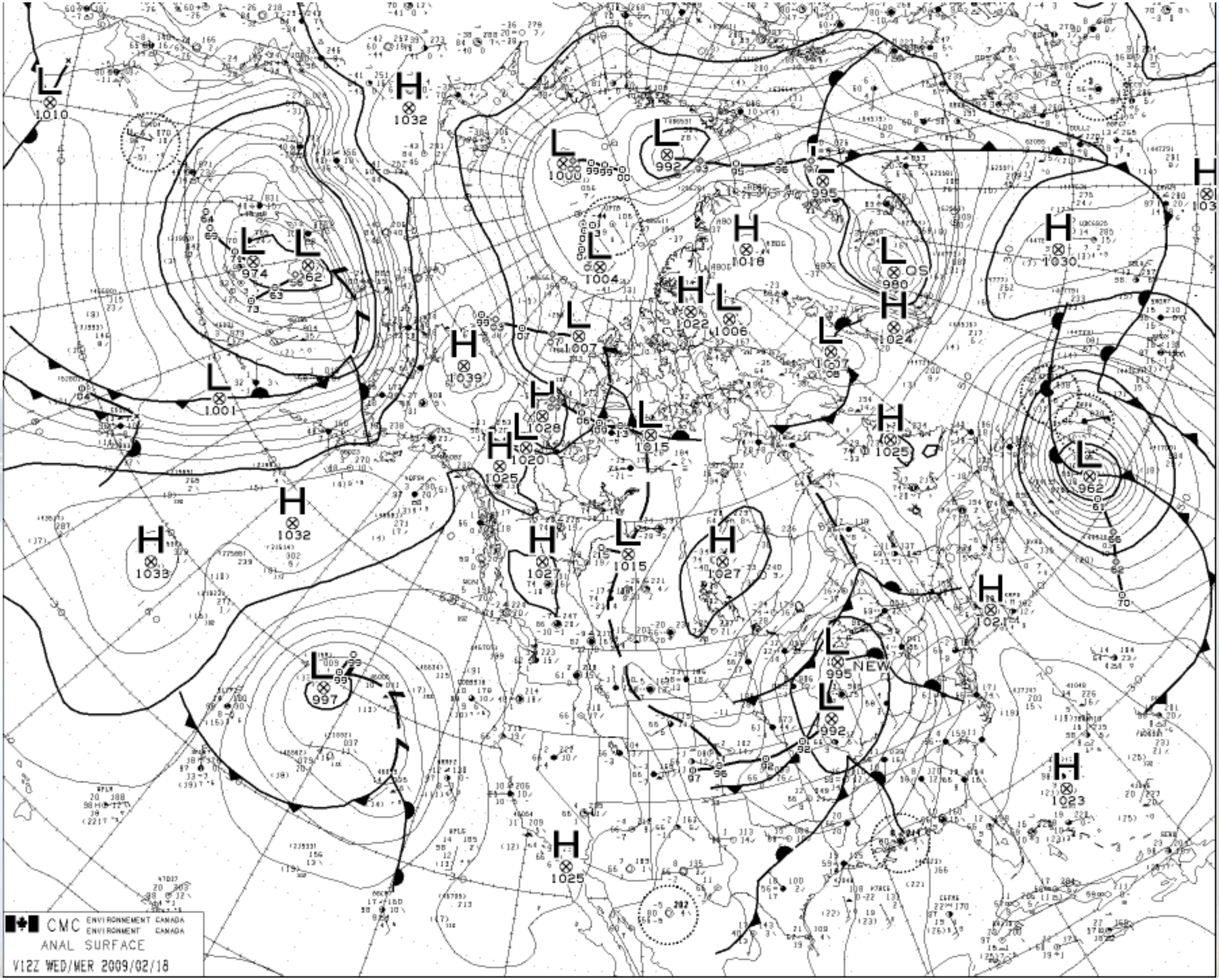
Hourly PM2.5, PM10 and SO2 Levels Recorded at Plaza
SO-2
PM2.5 rolling
PM25 (ug/m3)
PM10
SO2 concentrions and rolling PM2.5
PM2.5 Concentration (ug/m3)
0
10
20
30
40
50
60
0
15
30
45
60
75
90
105
120
135
150
2009-FEB-14 15:00
2009-FEB-14 21:00
2009-FEB-15 03:00
2009-FEB-15 09:00
2009-FEB-15 15:00
2009-FEB-15 21:00
2009-FEB-16 03:00
2009-FEB-16 09:00
2009-FEB-16 15:00
2009-FEB-16 21:00
2009-FEB-17 03:00
2009-FEB-17 09:00
2009-FEB-17 15:00
2009-FEB-17 21:00
2009-FEB-18 03:00
2009-FEB-18 09:00
2009-FEB-18 15:00
2009-FEB-18 21:00
2009-FEB-19 03:00
2009-FEB-19 09:00
2009-FEB-19 15:00
2009-FEB-19 21:00
2009-FEB-20 03:00
2009-FEB-20 09:00
2009-FEB-20 15:00
2009-FEB-20 21:00
2009-FEB-21 03:00
2009-FEB-21 09:00
2009-FEB-21 15:00
2009-FEB-21 21:00

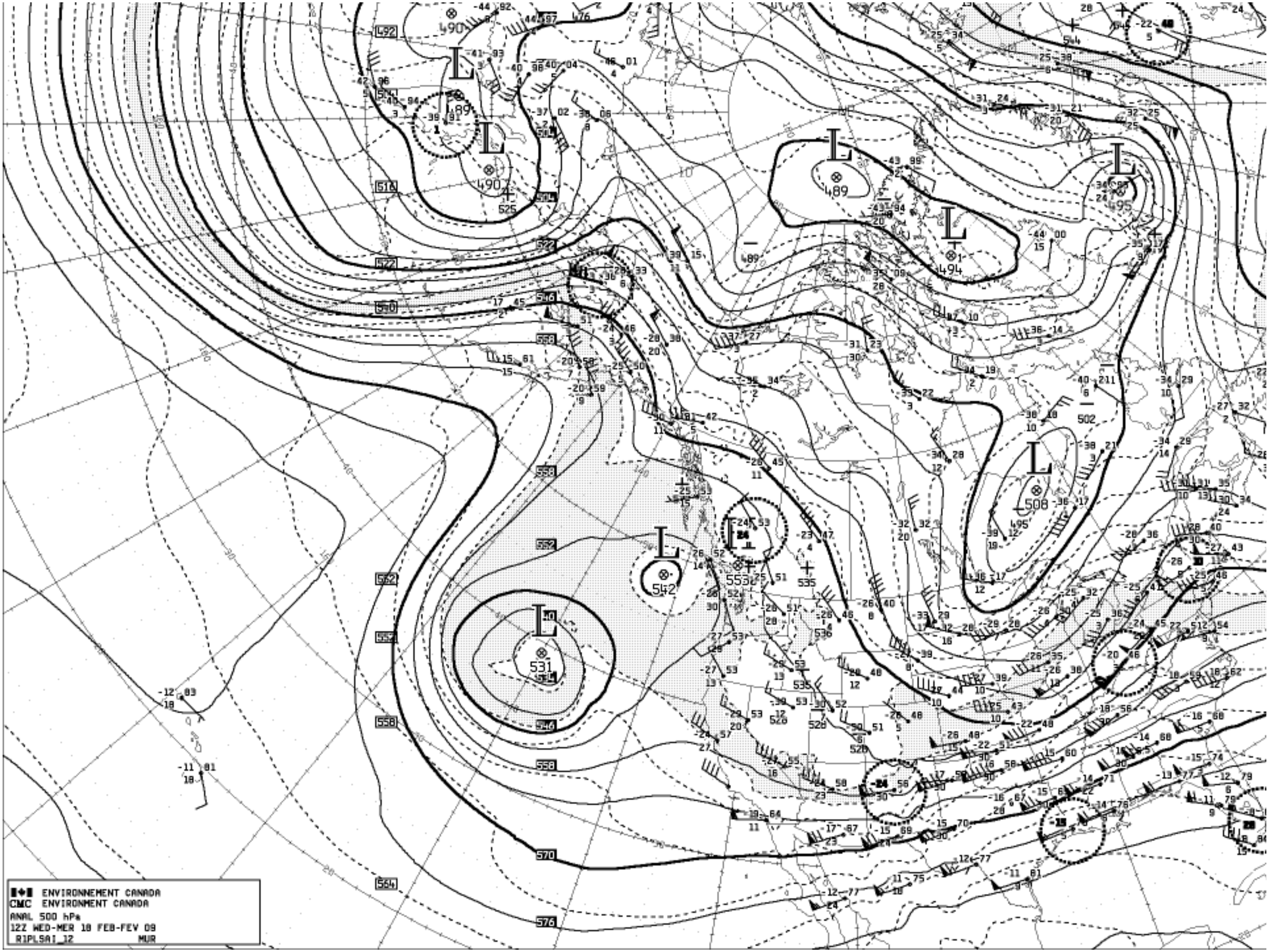

Hourly Temperature and Wind Speeds Recorded at Plaza
TEMP_MEAN
Wind speed
Temperature
Wind Speed (m/s)
10
5
0
-5
-10
-15
-20
-25
3.5
3
2.5
2
1.5
1
0.5
0
2009-FEB-14 15:00
2009-FEB-14 21:00
2009-FEB-15 03:00
2009-FEB-15 09:00
2009-FEB-15 15:00
2009-FEB-15 21:00
2009-FEB-16 03:00
2009-FEB-16 09:00
2009-FEB-16 15:00
2009-FEB-16 21:00
2009-FEB-17 03:00
2009-FEB-17 09:00
2009-FEB-17 15:00
2009-FEB-17 21:00
2009-FEB-18 03:00
2009-FEB-18 09:00
2009-FEB-18 15:00
2009-FEB-18 21:00
2009-FEB-19 03:00
2009-FEB-19 09:00
2009-FEB-19 15:00
2009-FEB-19 21:00
2009-FEB-20 03:00
2009-FEB-20 09:00
2009-FEB-20 15:00
2009-FEB-20 21:00
2009-FEB-21 03:00
2009-FEB-21 09:00
2009-FEB-21 15:00
2009-FEB-21 21:00

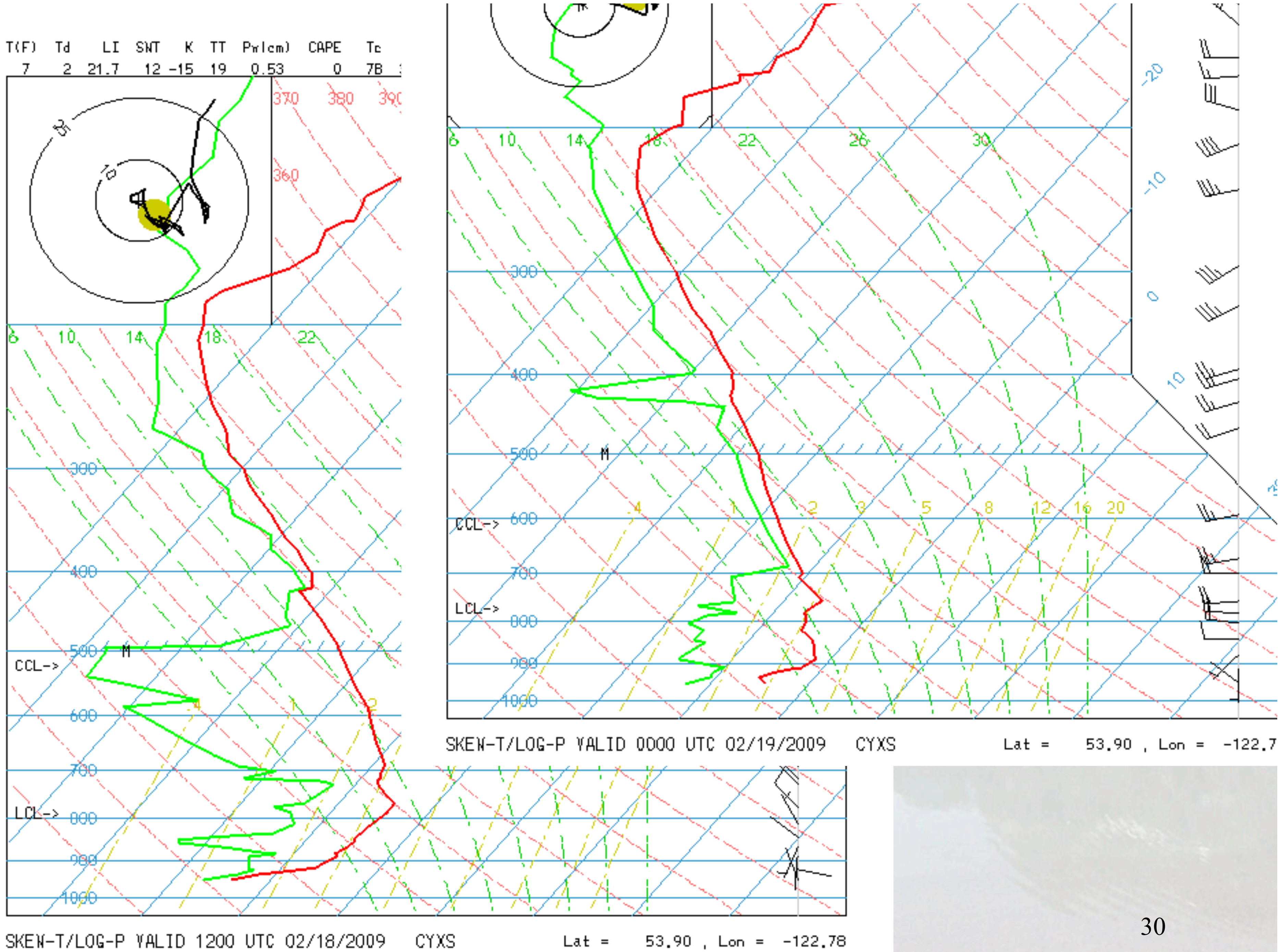

Hourly PM2.5 Levels and Wind Direction Recorded at Plaza
Wind Direction
PM25 (ug/m3)
Wind Direction
PM2.5 Concentration (ug/m3)
0
50
100
150
200
250
300
350
0
15
30
45
60
75
90
105
2009-FEB-14 15:00
2009-FEB-14 21:00
2009-FEB-15 03:00
2009-FEB-15 09:00
2009-FEB-15 15:00
2009-FEB-15 21:00
2009-FEB-16 03:00
2009-FEB-16 09:00
2009-FEB-16 15:00
2009-FEB-16 21:00
2009-FEB-17 03:00
2009-FEB-17 09:00
2009-FEB-17 15:00
2009-FEB-17 21:00
2009-FEB-18 03:00
2009-FEB-18 09:00
2009-FEB-18 15:00
2009-FEB-18 21:00
2009-FEB-19 03:00
2009-FEB-19 09:00
2009-FEB-19 15:00
2009-FEB-19 21:00
2009-FEB-20 03:00
2009-FEB-20 09:00
2009-FEB-20 15:00
2009-FEB-20 21:00
2009-FEB-21 03:00
2009-FEB-21 09:00
2009-FEB-21 15:00
2009-FEB-21 21:00


Vertical Profile of Temperature Recorded at 4:00 a.m. Over Prince George
Elevation (m)
Wind Speed (m/s)
Feb 18 a.m.
Feb 19 a.m.
Feb 20 a.m.
Feb 21 a.m.
5000
4600
4200
3800
3400
3000
2600
2200
1800
1400
1000
600
-30
-25
-20
-15
-10
-5
0


Vertical Profile of Wind Speed recorded at 4:00 a.m. Over Prince George
Elevation (m)
Wind Speed (knots)
Feb 18 a.m.
Feb 19 a.m.
Feb 20 a.m.
Feb 21 a.m.
5000
4600
4200
3800
3400
3000
2600
2200
1800
1400
1000
600
0
10
20
30
40
50


CMC ENVIRONNEMENT CANADA
ENVIRONMENT CANADA
ANAL SURFACE
V12Z WED/MER 2009/02/18


ENVIRONNEMENT CANADA
CMC ENVIRONMENT CANADA
ANAL 500 hPa
12Z WED-MER 18 FEB-FEV 09
R1PLSAI_12 MUR


T(F) Td LI SWT K TT Pw(cm) CAPE Tc
7 2 21.7 12 -15 19 0.53 0 78
CCL->
LCL->
SKEW-T/LOG-P VALID 0000 UTC 02/19/2009 CYXS Lat = 53.90 , Lon = -122.7
SKEW-T/LOG-P VALID 1200 UTC 02/18/2009 CYXS Lat = 53.90 , Lon = -122.78

Pollutant removal

- Gravitational settling removes particulates > 1 μm, with those > 10 μm settling quickly.
- Gaseous pollutants can be absorbed onto particles and removed with them.
- "tilted plume model" can be used to account for sedimentation where plume is tilted downward downwind

Dry Deposition

- Deposition (surface absorption) is a turbulent transfer (flux) of pollution to the ground, analogous to heat, water vapour, etc., fluxes.
- $F_p = - K_P \, \partial X / \partial z$
- Where F_p is the pollutant flux that depends on the eddy diffusivity of the matter (K_p) and on the pollutant (X) concentration gradient.

Wet Deposition

- Another mechanism for pollutant removal is through precipitation that scavenges pollutants from the air.
- Scavenging of particles or gases
  - in clouds (rainout), or
  - below clouds (washout)
- This effectively cleanses the air of gases and small particulates, some of which may become condensation nuclei for raindrops or snowflakes. Falling precipitation can also collect material ("washout").
- considered as an exponential decay process:

$$\chi(t) = \chi(0) \exp(-\Lambda t)$$

where Λ is the scavenging or washout coefficient

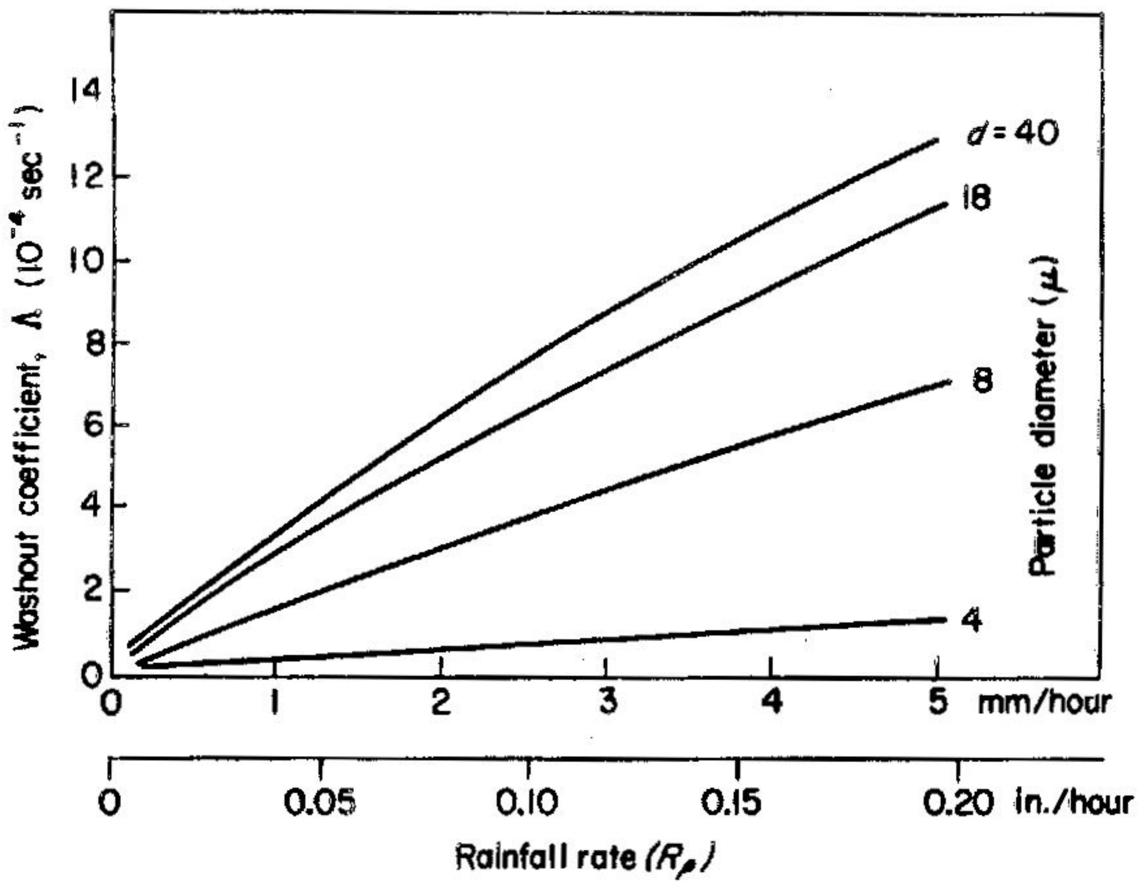


Fig. 18-6. Typical values of the washout coefficient as a function of rainfall rate and particle diameter. Source: After Engelmann (13).

Transformation

- Chemical transformations are often treated as exponential losses with time:

$$\chi(t) = \chi(0) \exp(-0.693\ t/L)$$

Where L is the "half life" of the pollutant [exp(-.693) = 0.5]

- A full treatment requires a model with chemistry

Processes of pollutant transformations

- This is a complex and not well understood topic (atmospheric chemistry).
- Two transformations of importance are:
- 1) transformations of the oxides of sulfur → sulfurous (London-type smog).
- 2) transformation of the oxides of nitrogen and hydrocarbons → photochemicals (L.A. - type smogs).

- SO_2 is a primary pollutant from the combustion of fuels → oxidizes to form sulfur trioxide (SO_3) that reacts with water vapour (H_2O) in the presence of catalysts to form sulfuric acid mist (H_2SO_4).
- H_2SO_4 may combine with other things to form sulfate particles which settle out.
- An exceptional example occurred in London, in 1952, where over a period of 4-5 days about 4000 people were killed.

- From action of solar radiation on nitrogen oxides in the presence of secondary pollutants (ozone, oxygen, NO_2, peroxyacetyl nitrates [PAN])
- Odour, brownish haze (NO_2 and particles), and throat irritations (O_3), aldehydes, PAN), plant damage (O_3, NO_x, PAN, ethylene)
- Fullest expression is in low latitude (lots of solar radiation) in urban environments (lots of cars).

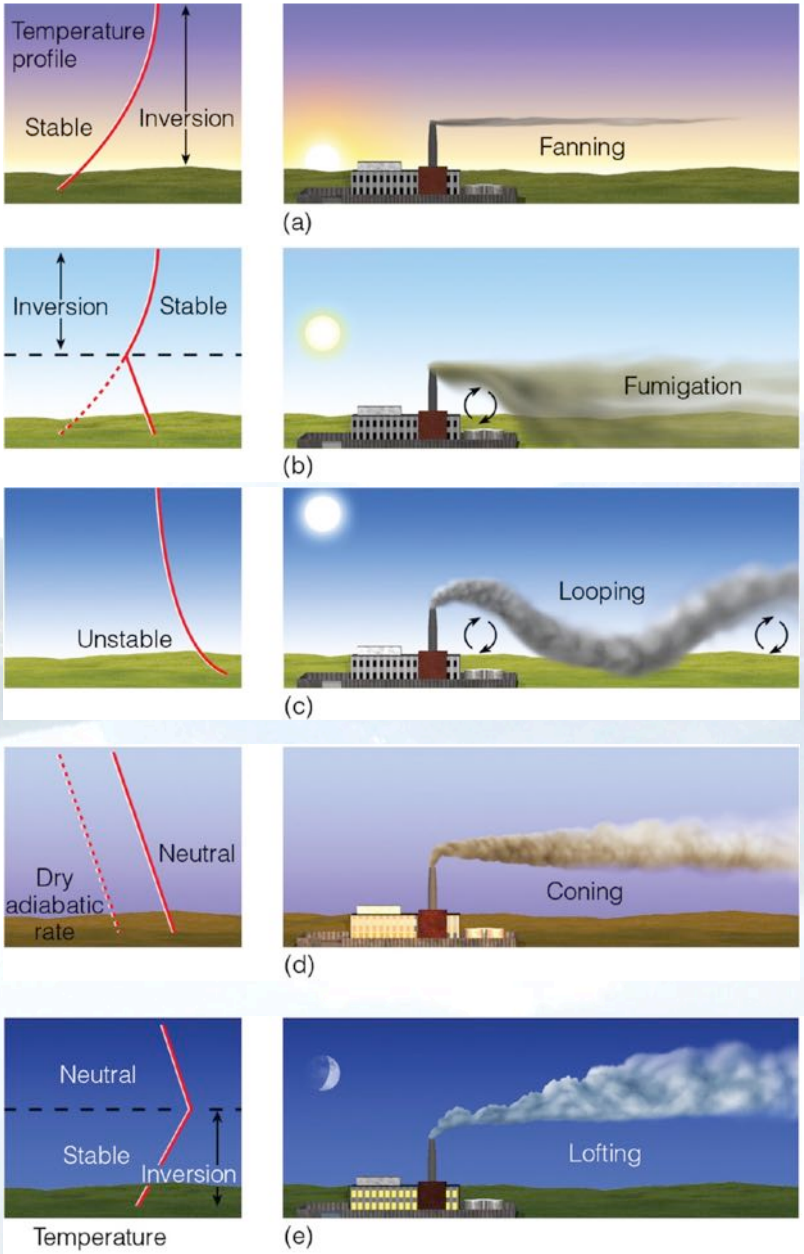


FIGURE 8 As the vertical temperature profile changes during the course of a day (a through e), the pattern of smoke emitted from the stack changes as well.

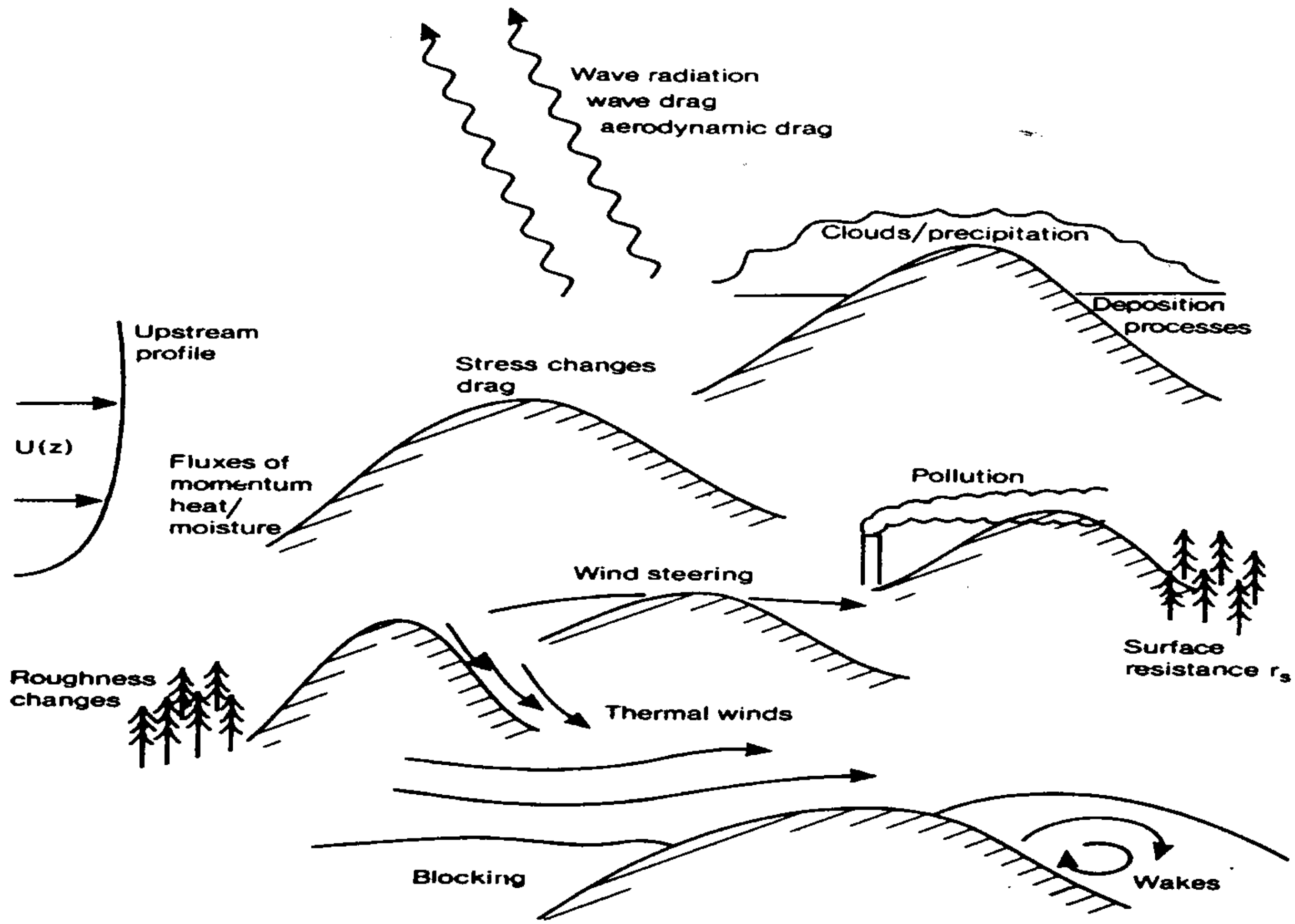
- There are 5 basic types of plumes:
  - Fanning - stable, little vertical mixing
  - Fumigation - stable layer aloft
  - Looping - daytime, unstable, large eddies
  - Coning - neutral, windy, forced isotropic convection
  - Lofting - most favourable dispersal condition - inversion at surface (evening)

Ahrens, Jackson, Jackson (2016)

2. Meteorology in the Mountainous Environment

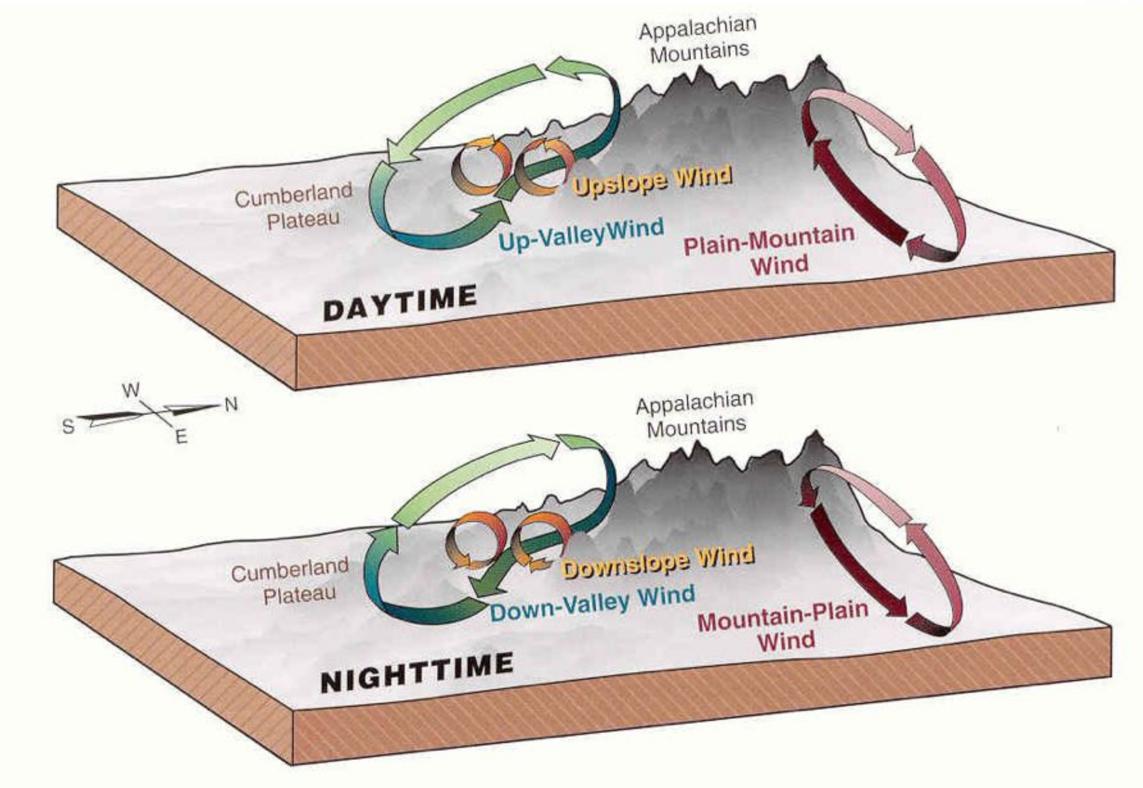
- Thermally driven circulations characterize the meteorology under slack synoptic conditions
- This is in contrast with the situation over homogeneous terrain
- Terrain is a fixed forcing – the mountains aren't moving, so these circulations are repeatable and we should be able to get them right

Processes occurring over Mountainous Terrain



Source: Carruthers and Hunt, 1990

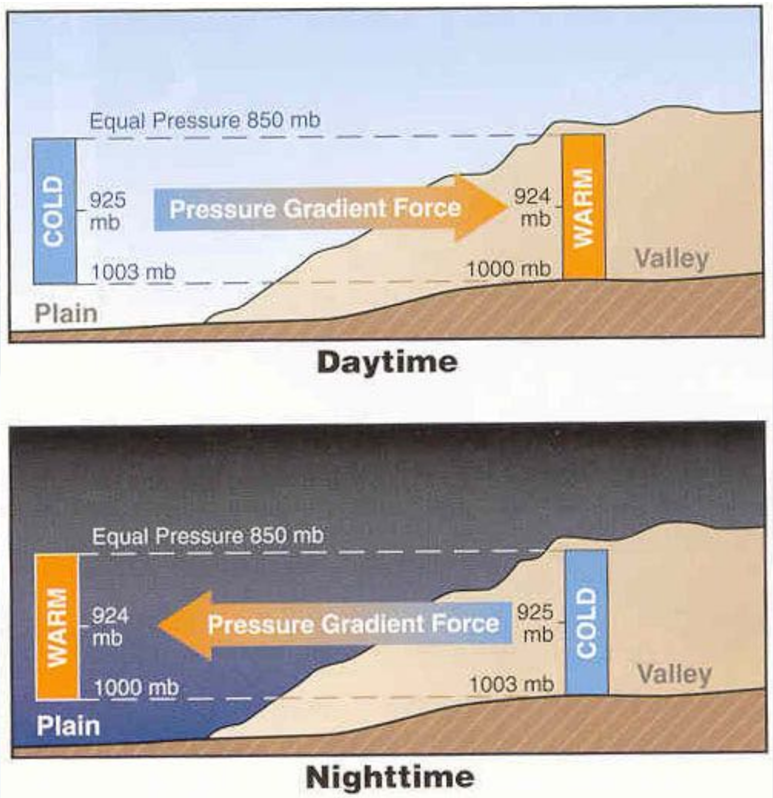
Mountain Wind System



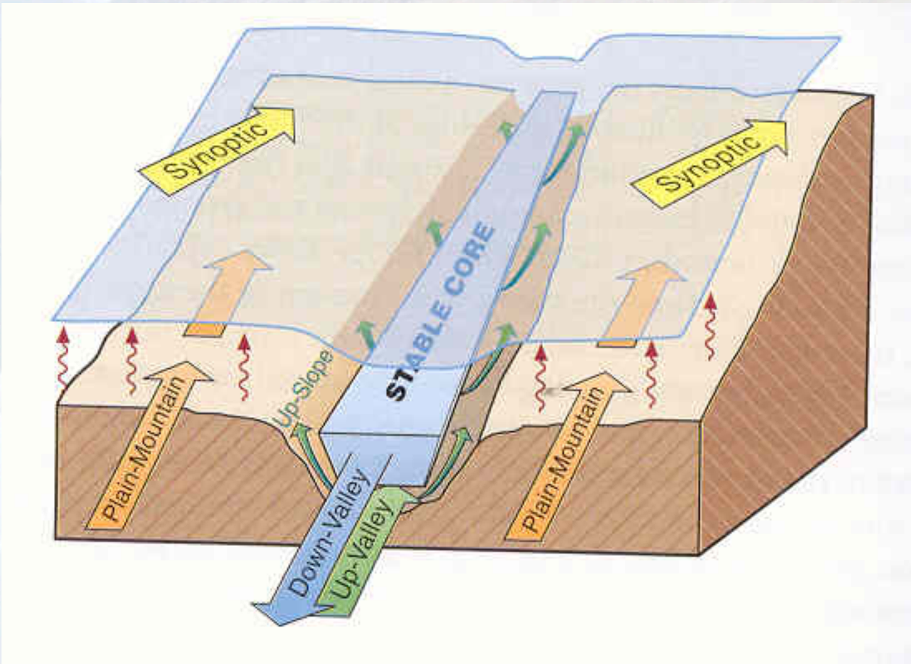
Source: Whiteman, 2000

- *Slope wind* driven by T contrast over slope and center
- *Along-valley wind* driven by T contrast along valley
- *Mountain-plain wind* driven by T contrast between mountain and plain
- *Cross-valley wind* driven by T contrast between valley sidewalls

Mountain – valley circulation

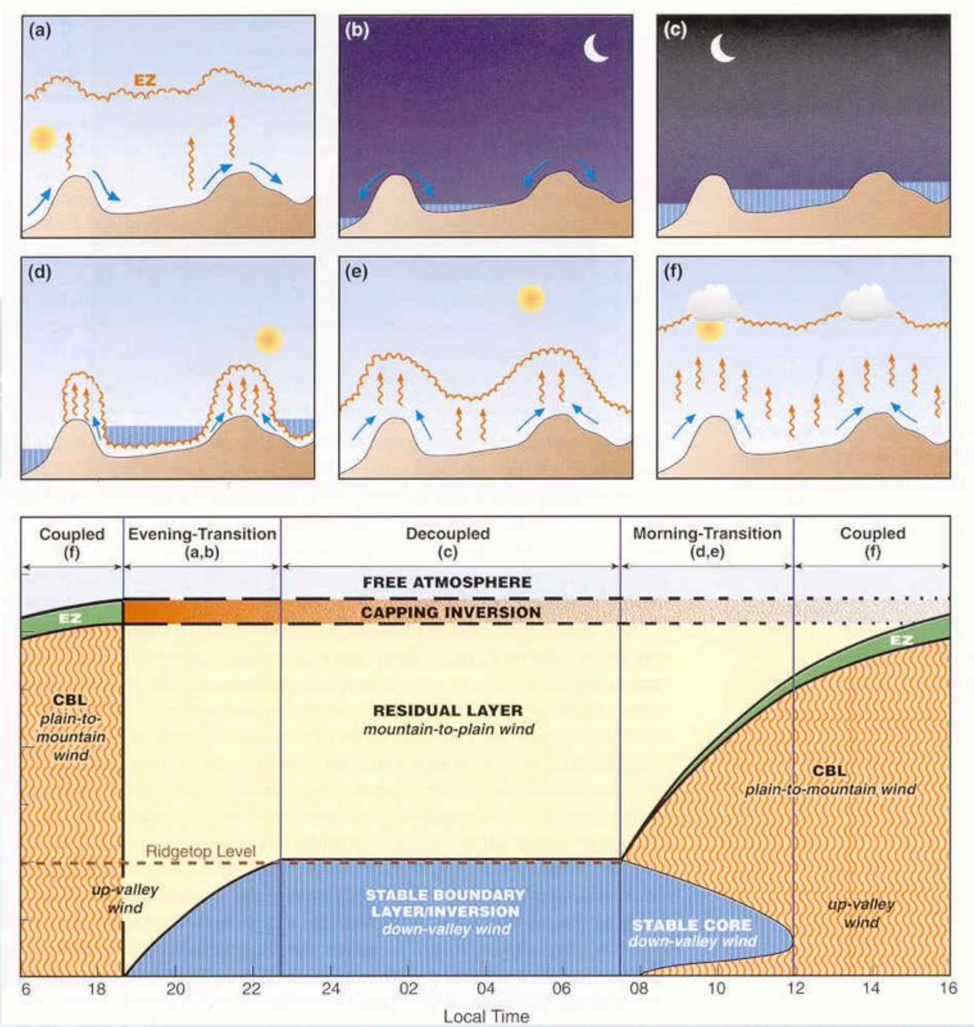


Source: Whiteman, 2000



Source:Whiteman, 2000

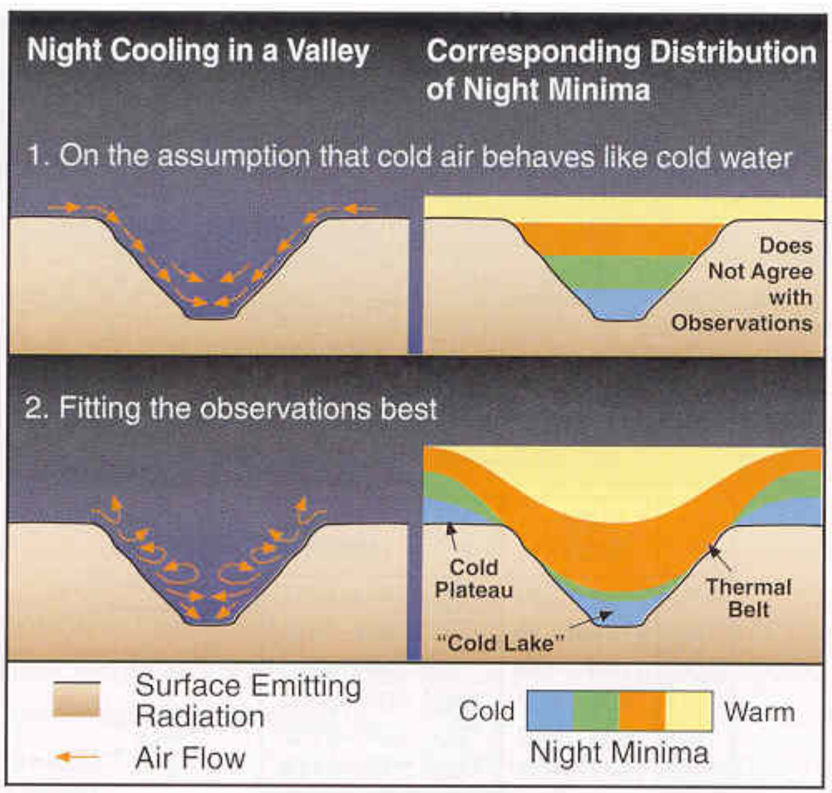
PBL Evolution in a valley



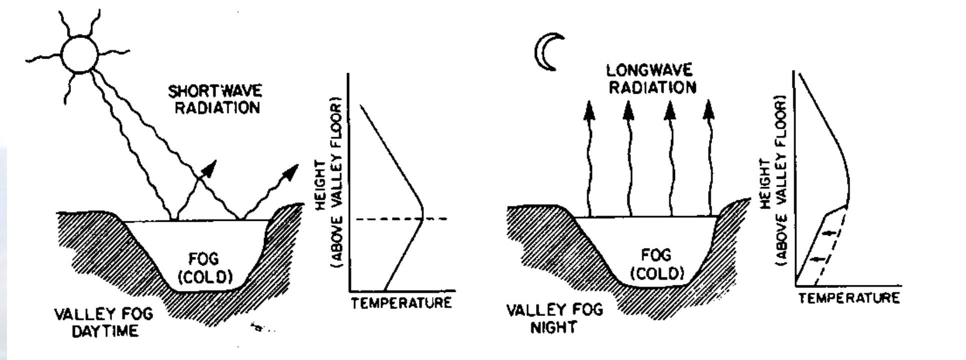
- Diurnal temperature and wind evolution over a valley
- During decoupled phase residual layer may be eroded by strong winds in free atmosphere

Source: Whiteman, 2000.

Cold air pooling

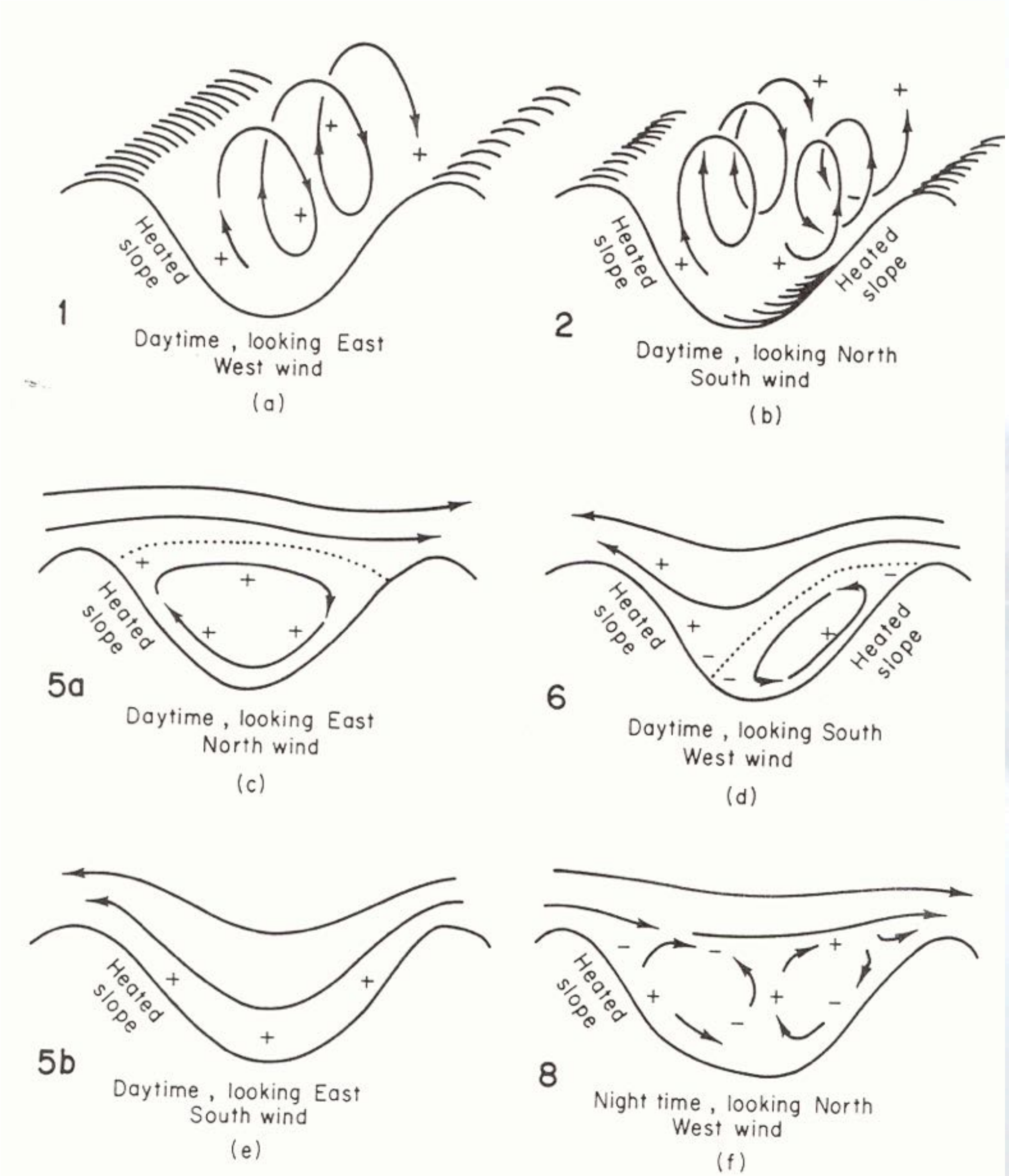


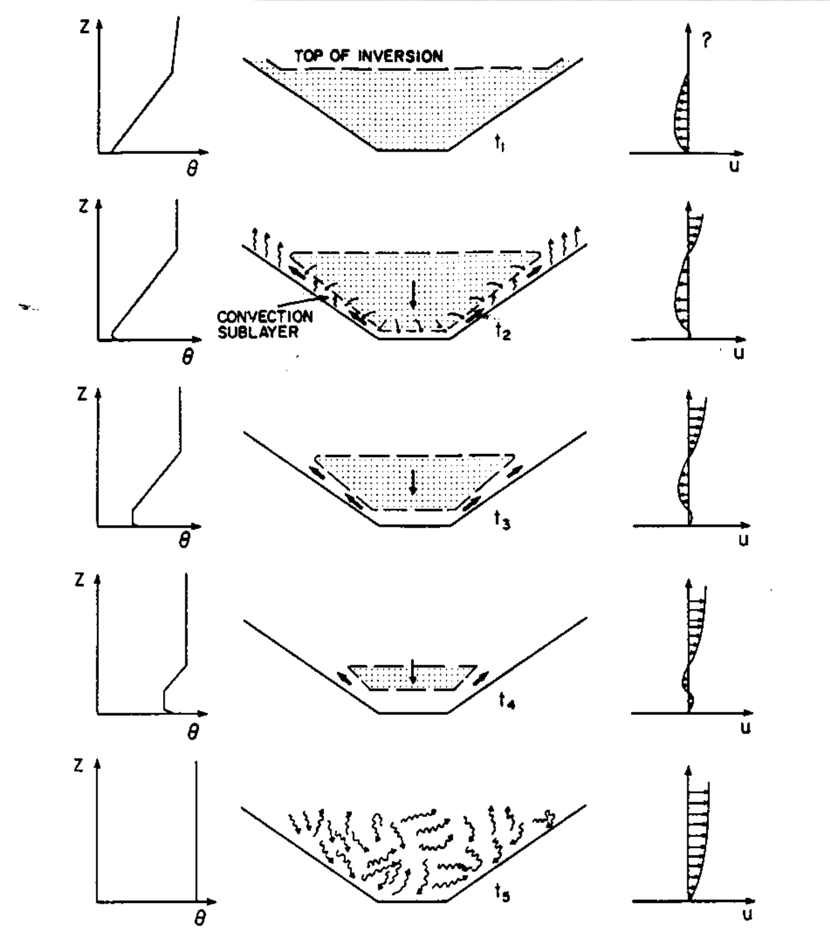
Source: Whiteman, 2000



Fog in Prince George 5 Oct 97

Valley Circulations





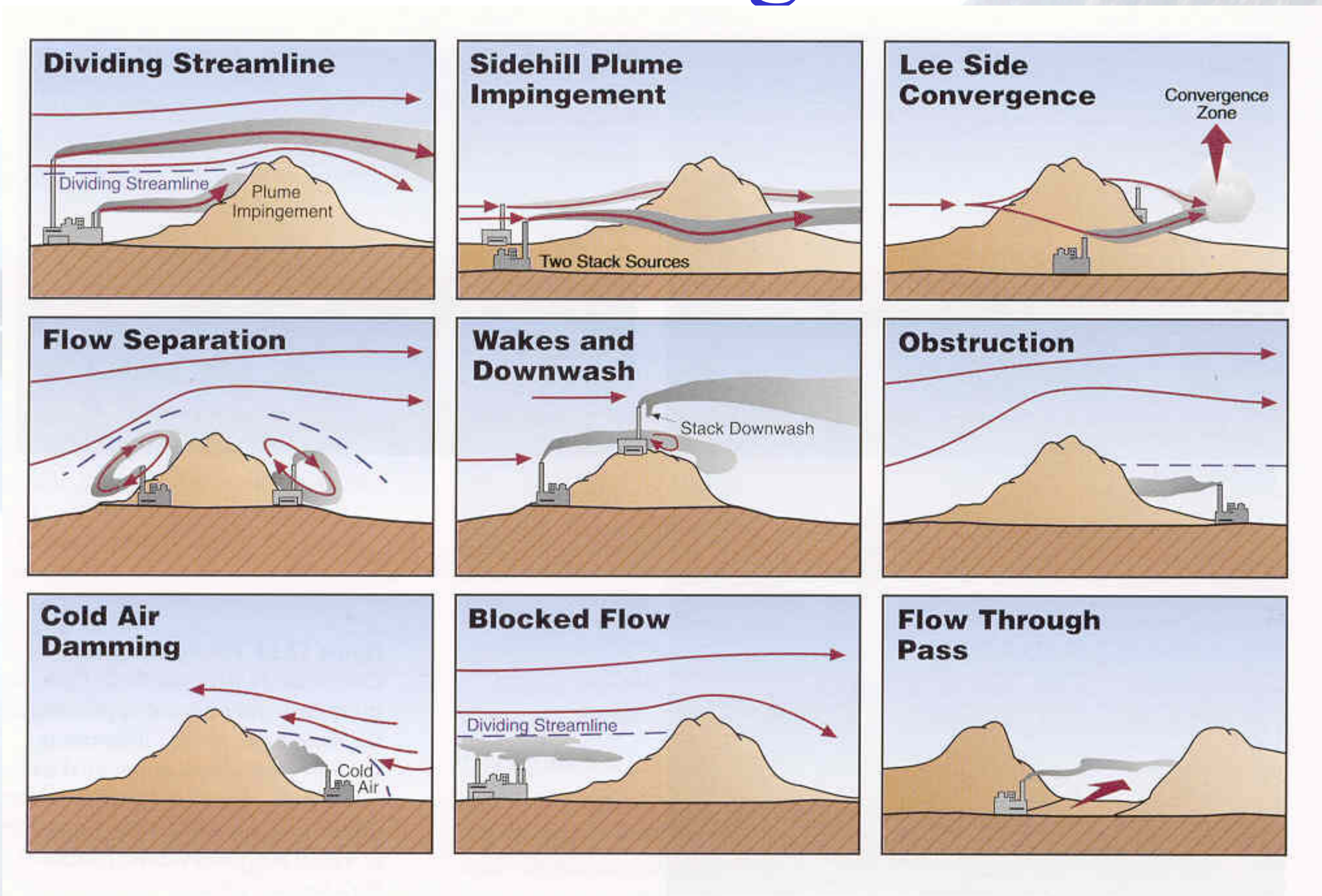
3. Air Quality Meteorology in the Mountainous Environment

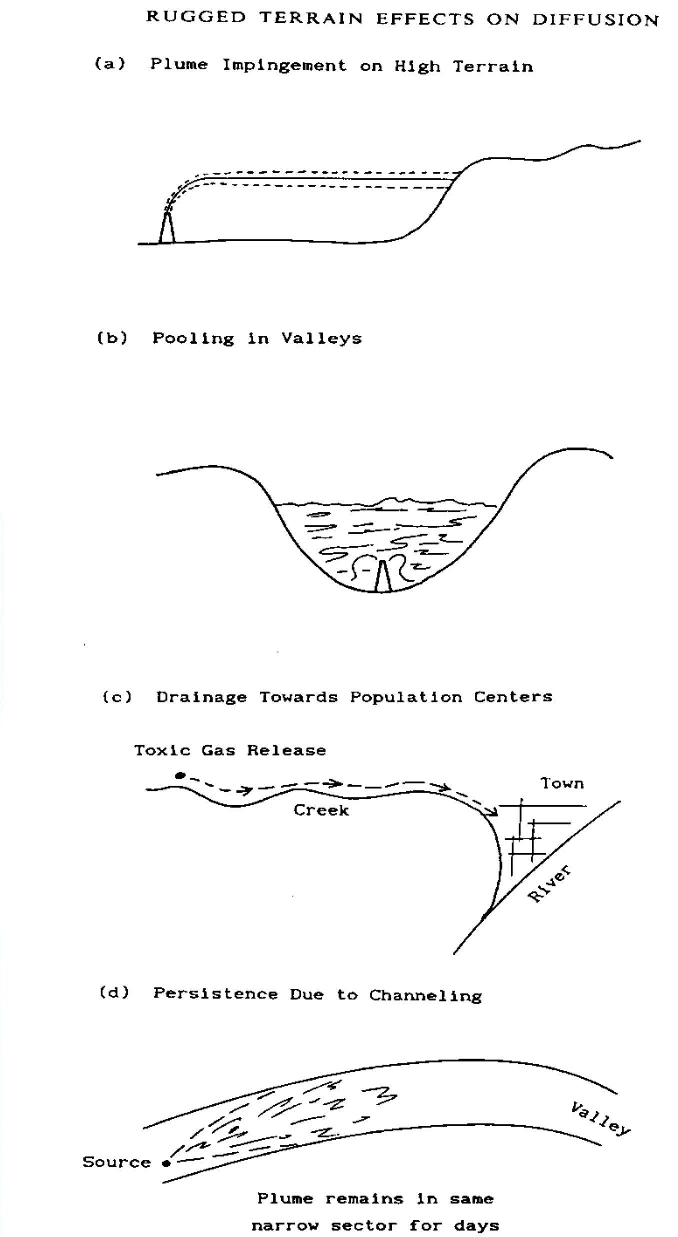
- What are the implications of complex terrain on Air Quality?
- As for non-mountainous terrain, AQ is an issue mainly during slack synoptic conditions → light winds, stable (nocturnal or subsidence inversions), typically anticyclonic conditions

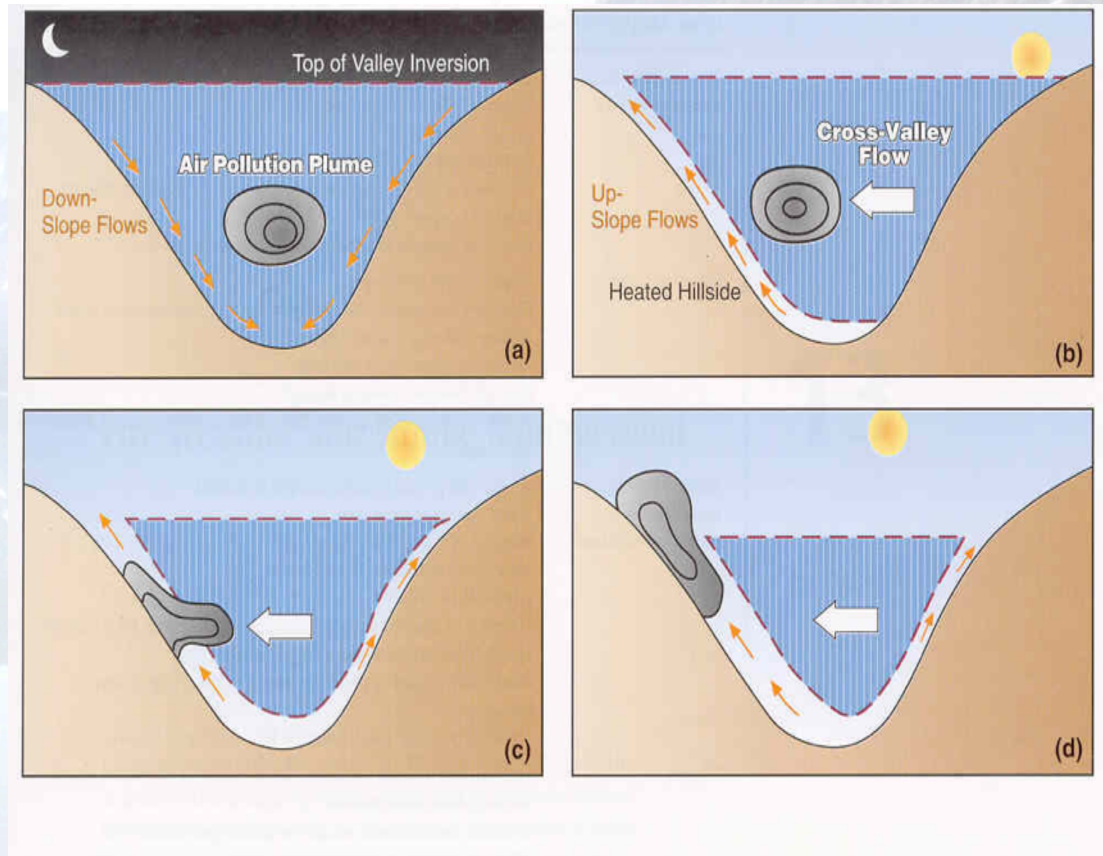
Dispersion models must:

- Account for plume impingement / steering / lifting by topography
- Account for thermal circulations induced by mountains

Plume impingement / steering / lifting




RUGGED TERRAIN EFFECTS ON DIFFUSION
(a) Plume Impingement on High Terrain
(b) Pooling in Valleys
(c) Drainage Towards Population Centers
Toxic Gas Release
Town
Creek
River
(d) Persistence Due to Channeling
Valley
Source
Plume remains in same
narrow sector for days


Top of Valley Inversion
Air Pollution Plume
Down-
Slope Flows
(a)
Cross-Valley
Flow
Up-
Slope Flows
Heated Hillside
(b)
(c)
(d)

Modelling

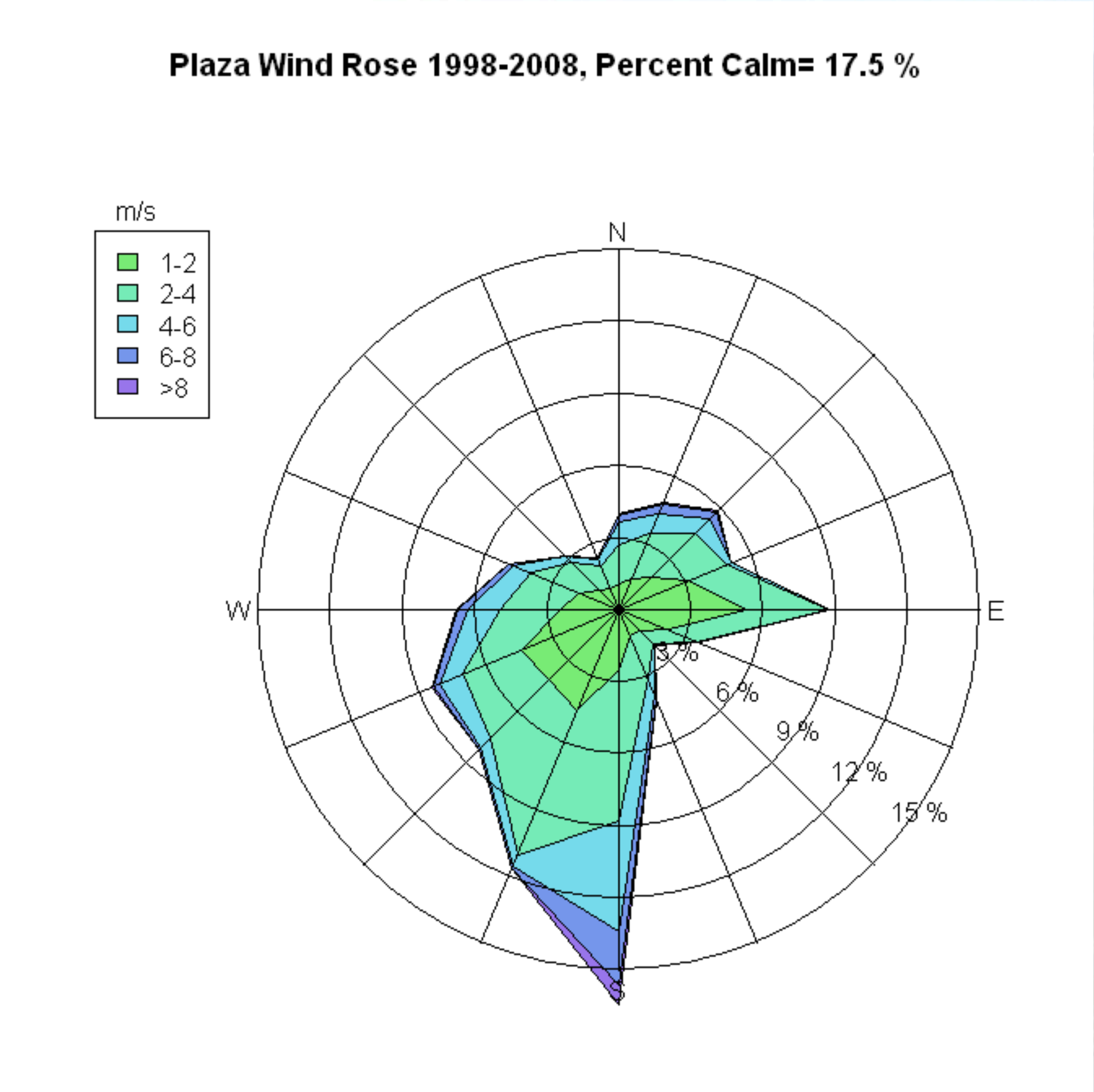
Traditional Gaussian Plume approaches to modelling dispersion are inadequate in mountainous terrain:

- most basic GPMs (no longer used in practice) did not account for plume impingement / lifting by elevated terrain
- Current GPMs may account for plume impingement / lifting, but not steering or circulations (if they do, the approach is somewhat arbitrary)

Air Pollution Climatology

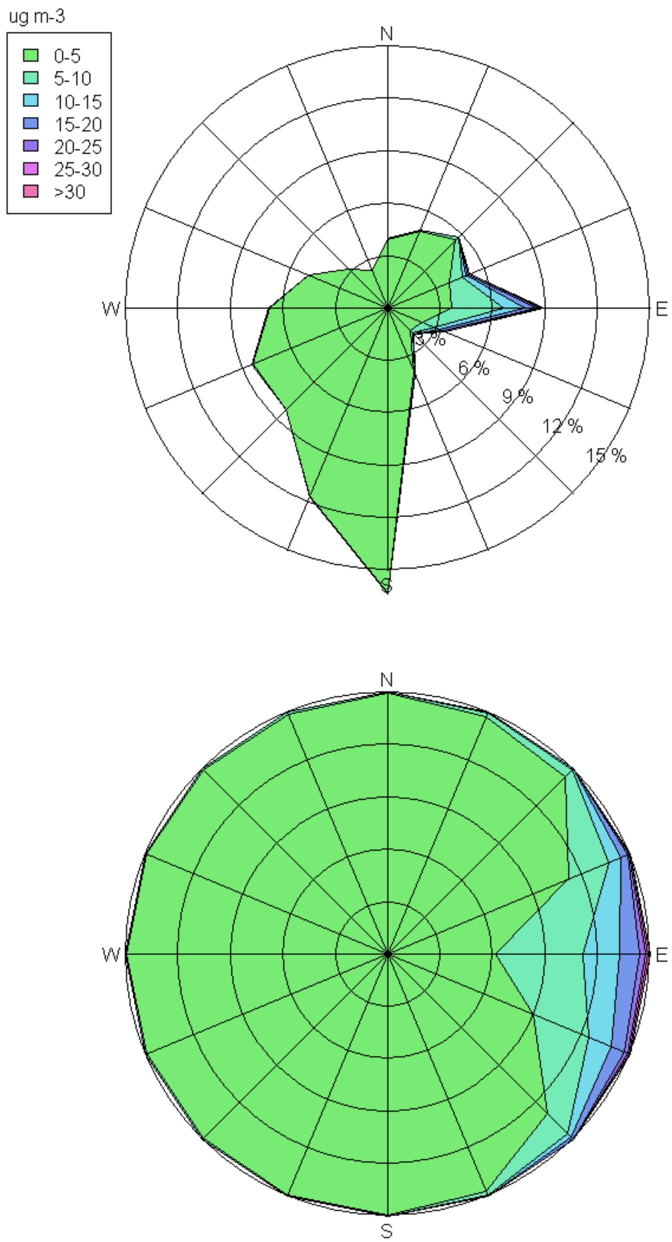
- Interpretation of air pollution data from a meteorological/climatological perspective
- Data typically available include hourly observations of:
  - Temperature, wind, humidity, clouds, pressure, visibility at many stations, also
  - Vertical profiles data from twice-daily radiosondes for information on mixing heights, etc
  - Derived data, such as frequency of stability class by wind speed and direction

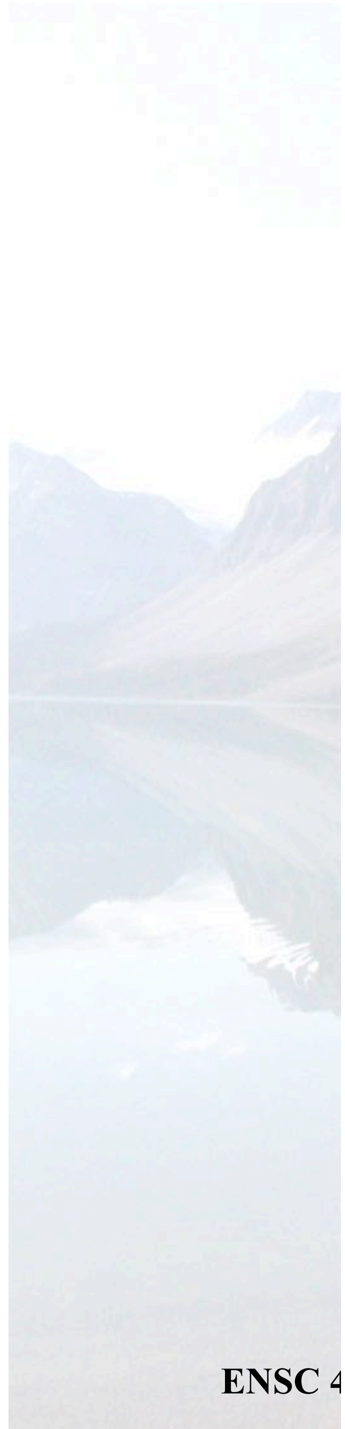
- Information of interest that can be derived from climatological records include:
  - Frequency of stagnation episodes
  - Inversion frequencies
  - Wind and pollution roses
  - Stability rose
  - Rose for dispersion model outputs…


Plaza Wind Rose 1998-2008, Percent Calm= 17.5 %
m/s
1-2
2-4
4-6
6-8
>8
N
E
S
W
3 %
6 %
9 %
12 %
15 %

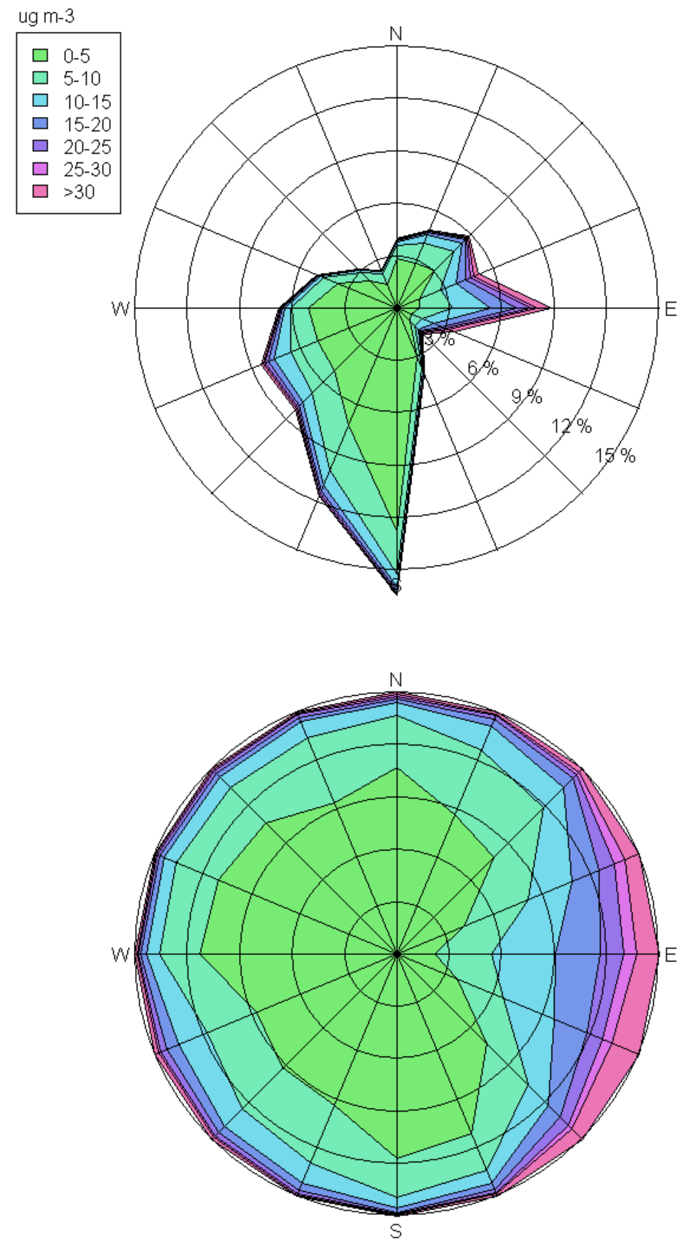
ENSC 412

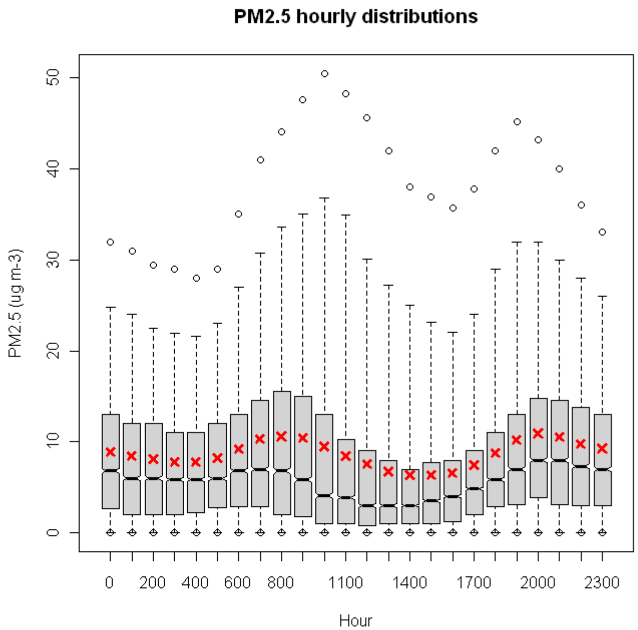
Plaza TRS Pollution Rose 2005

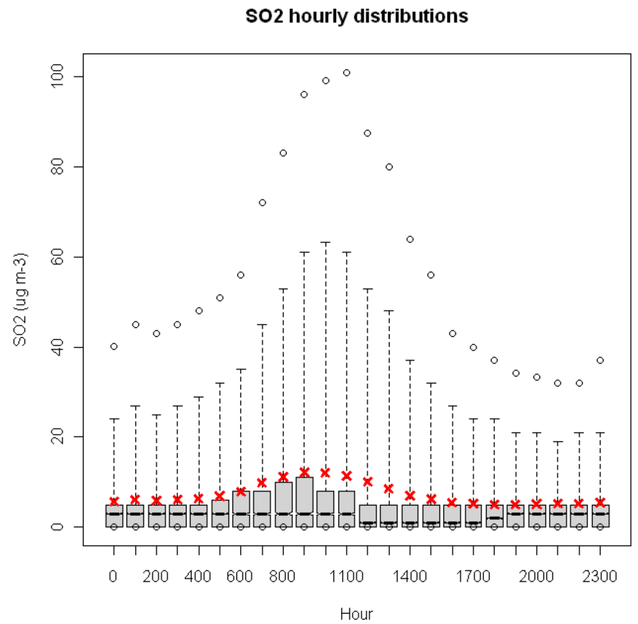


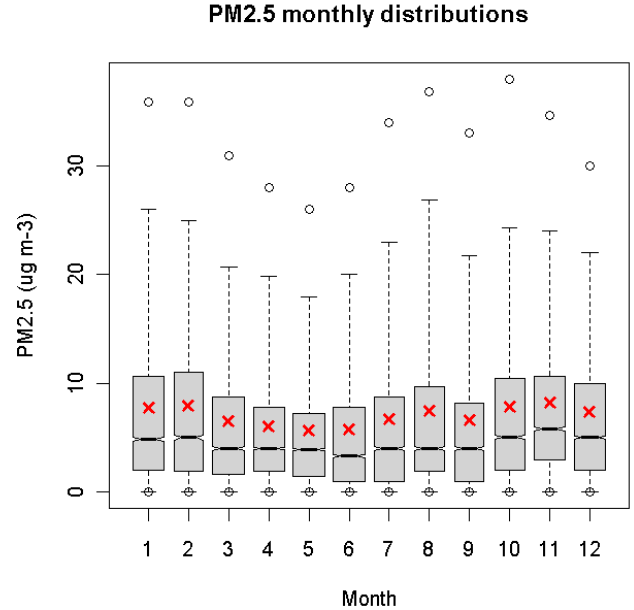


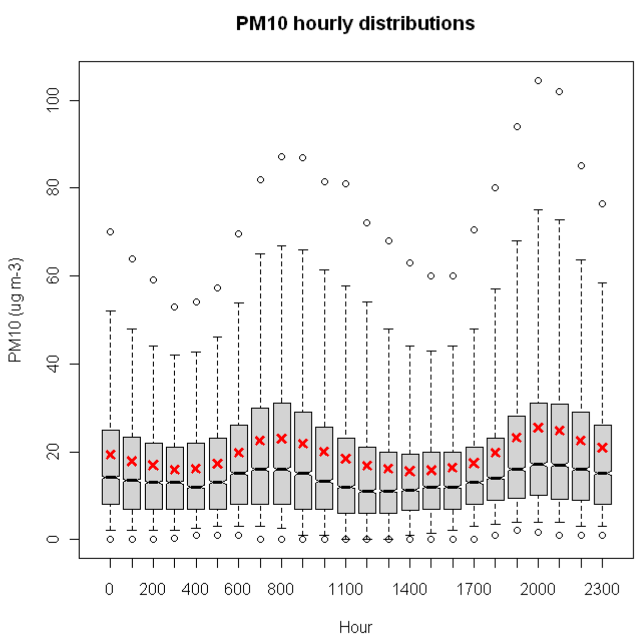
Plaza 1998-2008 PM2.5 Pollution Rose

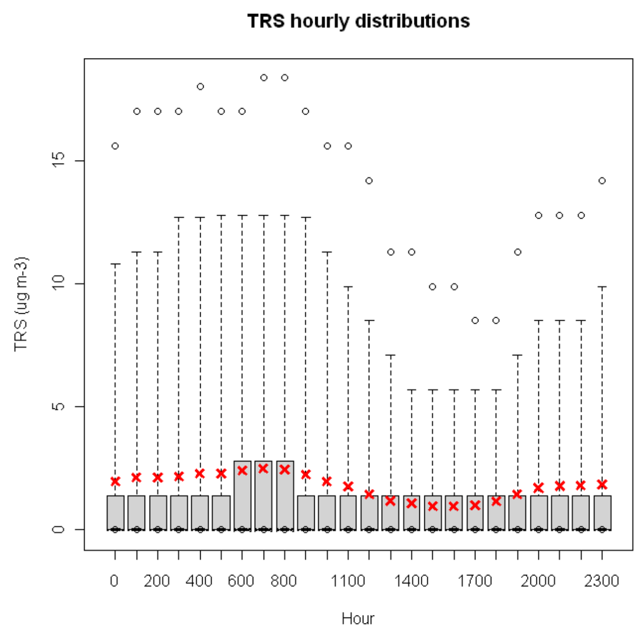


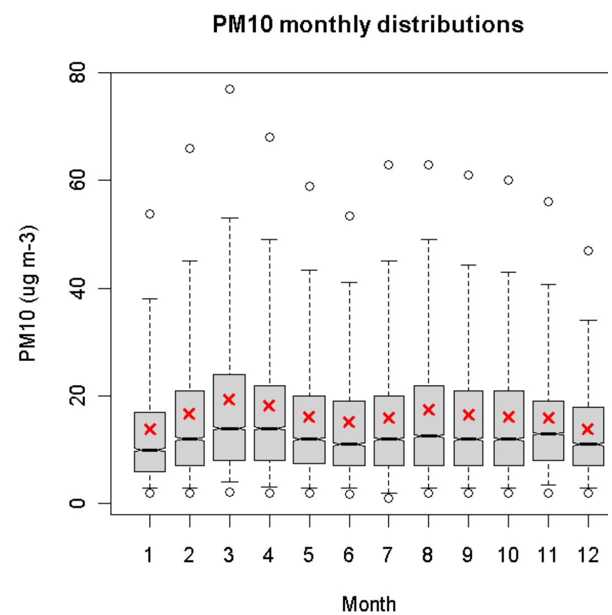

PM2.5 hourly distributions
PM2.5 (ug m-3)
0 10 20 30 40 50
0 200 400 600 800 1100 1400 1700 2000 2300
Hour


SO2 hourly distributions
SO2 (ug m-3)
0 20 40 60 80 100
0 200 400 600 800 1100 1400 1700 2000 2300
Hour


PM2.5 monthly distributions
PM2.5 (ug m-3)
0 10 20 30
1 2 3 4 5 6 7 8 9 10 11 12
Month


PM10 hourly distributions
PM10 (ug m-3)
0 20 40 60 80 100
0 200 400 600 800 1100 1400 1700 2000 2300
Hour


TRS hourly distributions
TRS (ug m-3)
0 5 10 15
0 200 400 600 800 1100 1400 1700 2000 2300
Hour


PM10 monthly distributions
PM10 (ug m-3)
0 20 40 60 80
1 2 3 4 5 6 7 8 9 10 11 12
Month

That's it!

Readings for next week

- Text Chapters 19, 20
- Millar, G.M, T. Abel, J. Allen, P. Barn, M. Noullett, J. Spagnol, P.L. Jackson, 2010: Evaluating human exposure to fine particulate matter Part II: Modeling. *Geography Compass*, **7,** 731-749**.** DOI 10.1111/j.1749-8198.2010.00344.x