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Meteorological Data for Air Pollution Assessment

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1 Introduction

Meteorological data are important as part of a complete air quality monitoring system. Local meteorological data have to be collected to explain the importance and impact of the different sources in an area and to understand the air quality measured. Meteorological data are needed from the surface layer of the atmosphere, normally collected along 10 m towers, and to the top of the atmospheric boundary layer. The latter information may be obtained from radiosonde data or from upper air data based on forecast models, supplied by the Institutes of Meteorology or by WMO.

As part of the air pollution monitoring programmes Automatic Weather Stations (AWS) is currently being installed at selected sites in the urban areas normally together with one of the automatic air quality monitoring stations. Meteorological "surface data" such as winds, temperatures, stability, radiation, turbulence and precipitation are being transferred to a central computer via radio communication, telephone or satellite together with air quality data.

Continuous measurement of meteorology should include sensors for the most important parameters such as:

1. Wind speeds,
2. wind directions,
3. relative humidity,
4. temperatures or vertical temperature gradients,
5. net radiation,
6. wind fluctuations or turbulence,
7. precipitation and
8. atmospheric pressure.

Meteorological data will for instance be needed as input to the air pollution planning tool (such as the AirQUIS database), both for interpretation of air quality data and for modelling purposes.

2 Dispersion and meteorology

The weather on all scales in space and time acts on the transport and dilution of air pollutants and plays different roles on the air quality that we measure and feel.

Meteorology specifies what happens to a plume (or puff) of air pollutants from the time it is emitted from its source until it is detected at some location (at a receptor). The motion of the air dilutes the air pollutants emitted into it. Given a known emission rate, it is possible to calculate how much dilution occurs as a function of meteorology or atmospheric conditions, and the resulting concentrations downwind of the source. This will require some basic knowledge of meteorology and its effects on the dispersion of air pollutants.

2.1 Wind

Local wind and temperature patterns play a significant role on the dilution of air pollution. The transport of pollutants emitted into the atmosphere is a function of the local (average) wind direction. The dilution of pollution is mainly a function of wind speed and turbulence. This wind is again influenced by:

- Topography, which channels the wind and modify the local wind directions,
- Vegetation and buildings, which influence on the surface friction and reduce wind speed at the surface,
- Net radiation and radiation balance, which influence on the atmospheric stability, and thus on the vertical wind profile,
- Local and mesoscale sources of heating and cooling setting up thermally driven local winds.

All these factors interact to change the dispersal conditions of the atmosphere.

The transport of the emitted air pollution is directed along the trajectory of the air parcel in which the pollutants were emitted. The trajectory is a function of wind direction and wind speed in the wind field. The dilution of pollutants is a function of the atmosphere's turbulent conditions, which are presented by a 3-dimensional variation in wind direction and wind speed. Turbulence is usually defined by fluctuation of the wind with spatial dimensions less than the pollutant plume.

The variation of wind on all scales is the most important factor deciding the air pollution concentration at a receptor location. The wind observed at a certain receptor is the sum of several effects:

- Large scale wind patterns (geostrophic)
- Friction (roughness change)
- Thermally driven local winds
- Radiation balance
- Topographical features (deformation, channelling...)

2.1.1 Large scale wind patterns

Wind is a result of equilibrium produced by pressure, Coriolis and friction forces. Weather maps show regions of high and low pressure and also denote wind direction and wind speed. The pressure forces are caused directly by the existence of high and low pressure regions in the atmosphere. In the Northern Hemisphere the air blows counter clockwise around low-pressure centres while in the Southern Hemisphere the air blows clockwise.

High-pressure regions are called anticyclones and these are often the source of temperature inversions. An inversion limits the atmosphere's potentiality for dilution of pollutant emissions.

2.1.2 Terrain induced air flow

During the diurnal circulation in mountainous regions, three-dimensional circulation can form within and just above the valleys. Complex cross-valley-axis flow (anabatic/katabatic slope winds), and along valley-axis-flow (mountain/valley winds), may be combined to three-dimensional mountainous circulation.

2.1.3 Mountain and valley winds

During the night, radiative cooling of the mountainsides cool the air adjacent to the surfaces, resulting in cold down slope or katabatic winds. These winds are normally very shallow (2 to 20 m), and the normal velocities are within the order of 1 to 2 m/s.

Above the valley floor drainage flow is a gentle return circulation of upward moving air that diverges toward the ridges. The chilled and heavy air flows into the valley and collects as a cold pool. Although some of the cold air flows down the valley axis, some can remain in the valley depending on the topography. The resulting pool is often stable stratified throughout its depth, and is sometimes called a valley inversion. The potential temperature profile indicates the shallow inversion layer that started to build up in the valley bottom during the night. The radiative cooling of the ground continued throughout the night creating a deep cold pool throughout the valley. Pollutants emitted into this inversion can build to high concentrations because of very slow dispersion in the vertical, and can be hazardous to people, animals, and plant life on the slopes.

During the sunny hours after sunrise, the incoming solar radiation will warm the mountain/valley sides and the air in contact with it faster than the air at some distance from the slope. This differential heating sets up a circulation, which is akin to the sea breeze and is called the anabatic winds. Because of this instability in the lower layers of air set up by the differential heating, the warm air will stream toward and up the valley sides.

2.1.4 Drainage winds

At night, the cold winds flowing down the valley onto the plains are known as mountain winds or drainage winds. Depths range from 10 to 400 m, depending on the size and flow constrictions of the valley. Velocities of 1-5 m/s have been observed and these winds are occasionally intermittent or surging. The return gentle circulation of warmer air aloft is called the anti-mountain wind, with velocities of about half of the mountain wind, and depth of about twice as much.

2.1.5 Sea and land breeze

The large heat capacity of oceans and lakes reduces water-surface temperature change to near-zero values during a diurnal cycle. The land surface, however, warms and cools more dramatically because the small molecular conductivity and heat capacity in soils prevents the diurnal temperature signal from propagating rapidly away from the surface. As a result, the land is warmer than water during the day, and cooler at night. This situation causes sea breezes.

The general feature is that during the morning there is little difference in temperature between land and sea. During mid-morning, however, air begins to rise over the warm land near the shoreline as a result of the solar heating from the sun, and cooler air from the water flows in to replace it. A return circulation (the anti-sea-breeze) aloft brings the warmer air back out to the sea where it descends toward the sea surface to close the circulation. The depth of the sea breeze have been observed to be on the order of 100 to 500 m, and the total circulation depth including the return circulation can range from 500 m to 2000 m.

At night, land surfaces usually cool faster than the neighbouring water bodies, reversing the temperature gradient that was present during the day. The result is a land breeze; cold air from land flows out to sea at low levels, warms, rises and returns aloft towards land (anti-land-breeze) where it eventually descends to close the circulation.

2.2 Turbulence

The atmosphere can disperse gases and particulate matter rapidly because it is turbulent. Turbulent flow can be defined as having the ability to disperse embedded gases and particles at a rapid rate. Turbulence is the primary process by which momentum, heat, and moisture are transported into the atmosphere from the surface of the earth and then mixed in time and space.

Turbulence can be visualised as consisting of irregular swirls of motion called eddies. Usually turbulence consists of many different size eddies superimposed on each other. Thus, a continuous hierarchy exists from the largest down to the smallest eddies, with molecular diffusion occupying the bottom of the scale.

The effect of eddy motion is very important in diluting concentrations of pollutants. An air parcel that is displaced from one level in the atmosphere to another can carry both momentum and thermal energy with it. Obviously it will also carry the pollution emitted into the air parcel. Hence, the turbulent motions in both the horizontal and vertical directions will diffuse smoke and pollution.

The effect of different eddy sizes on a plume is shown in the Figure below.

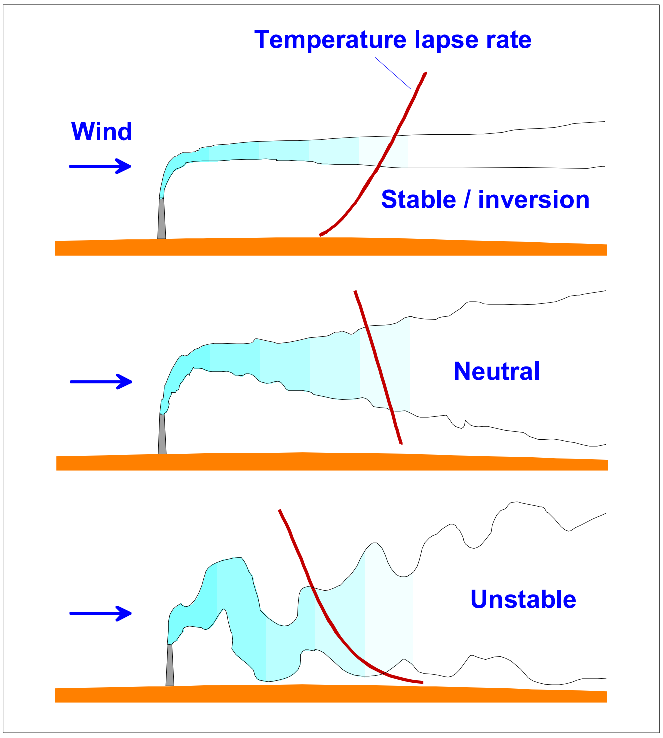

Figure1: (a) Plume dispersing in a field of small eddies in a stable atmosphere (inversion). The plume will move in a relatively straight line, with gradual increase of its cross section.

(b) Plume dispersing in a field of well defined large eddies (near neutral atmospheric conditions). Turbulent eddies with typical size less than the plume dimension will disperse the plume effectively.

(c) Plume dispersing in a field of large and various sized eddies. This is atypical daytime situation with unstable atmospheric conditions. The dispersed plumes will both grow and meander as it moves downwind.

Atmospheric turbulence depends in general on the magnitude of three factors: mechanical effects or the roughness of the ground, horizontal and vertical wind shear, and thermal instability. These factors are described separately in the following chapters.

2.2.1 Mechanical induced turbulence

Mechanical induced turbulence is caused by wind flow over uneven and rough surfaces. Turbulence is generated by mechanical shear forces at a rate proportional to $(\partial u/\partial z)^2$ (the wind speed profile). The wind profile gradient is dependent upon the surface roughness and the stability of the atmosphere. The velocity profile can be described using the power law:

$$\overline{U}_z = \overline{U}_0 \left(\frac{z}{z_0} \right)^m$$

where m varies between 0.12 and 0.50, depending on the atmospheric conditions.

2.2.2 Thermally induced turbulence

Convection or thermally induced turbulence is defined as predominantly vertical atmospheric motion resulting in vertical transport and mixing of atmospheric properties. Convective eddies or turbulence arises from hydrostatic instability as the result of surface heating (i.e. solar heating of the ground during sunny days causes thermals of warmer air to rise). These eddies are largest and occurs at a lower frequency than eddies produced by mechanical turbulence. Note that convective turbulence, unlike mechanical turbulence, is indirectly related to wind shear and strongly related to stability

2.3 Atmospheric stability

In its simplest terms, the stability of the atmosphere is its tendency to resist or enhance vertical motion, or alternatively to suppress or augment existing turbulence. Stability is related to both wind shear and temperature structure in the vertical, but it is generally the latter, which is used as an indicator of the condition.

The atmospheric stability, or the atmospheric dispersion conditions, can be classified as unstable (U), neutral (N) or stable (S). A short description of the three individual classes of atmospheric stability is given below.

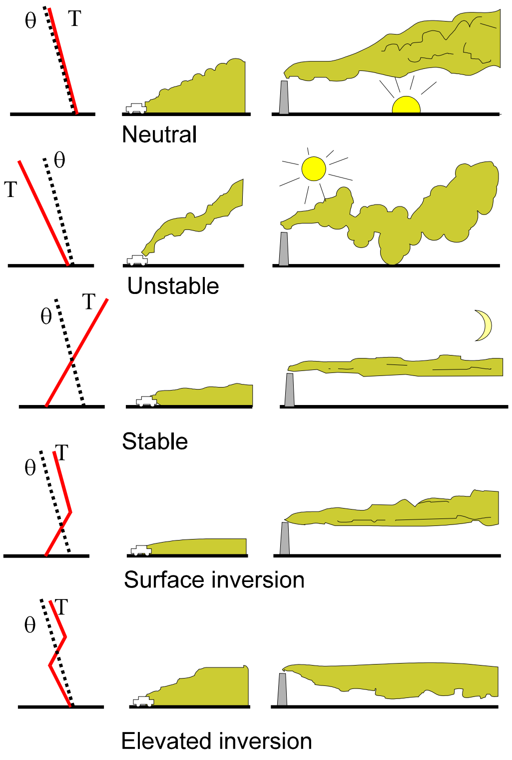

Figure2: Schematic presentation of the atmospheric stability and the corresponding dilution of air pollutants above ground level.

- Neutral atmospheric stability (N) occurs at moderate to high wind speeds that are usually connected to overcast skies. High wind speeds and good mechanical turbulence/mixing result in good horizontal and vertical mixing of the smoke plume.

- Unstable atmospheric stability (U) is common on days with strong solar heating and low wind speed, or when cold air is being transported over a much warmer surface. The sun warms the underlying surface and vertical turbulent eddies are set up causing vertical dispersion of the smoke plume. For emissions at ground level or just above ground level, the concentrations will dissolve quickly. For stack emissions, elevated concentrations may occur at the ground because of the turbulent motion of the lowest level of air.

- Stable stratified atmosphere (Ls, S) is usually confined to clear nights and winter situations with cooling of the ground and the lower layers of air. In a stable stratified atmosphere the temperature increase with height, and hence, the vertical dispersion is poor. In situations when relatively warm air from the sea is transported over land, the lower level of air will be stable stratified. This result in poor dispersion of the smoke plumes both horizontally and vertically. For ground level sources this situation is critical because of poor vertical dilution and hence, enhanced ground level concentrations of pollution. For stack emissions, poor vertical dilution result in high-level pollution concentrations being transported far before it touches ground.

3 Meteorological data from forecast models

In areas where meteorological data are not being measured in situ, data may be generated from numerical weather forecast models. Numerical forecast models have been developed to estimate the wind fields, which have been used as input to the AirQUIS air pollution dispersion modelling system to estimate concentration distributions for the next 24 and 48 hours.

The wind field has been estimated based on the European HIRLAM50 numerical weather prediction model. The wind patterns predicted by HIRLAM50 is then compared to locally observed winds and turbulence, so that future predictions of weather patterns can be used to estimate the local wind- and turbulence patterns and thus the air pollution concentrations in the receptor points where statistical relationships have been established.

The results from the HIRLAM 50 model with 50 km or 10-km resolution have also been used as input to a mesoscale model, MM5, to produce a more detailed wind field. The development of the MM5 model is a continuation of a development that started at NCAR in the seventies. The PSU/NCAR mesoscale model is a limited-area, hydrostatic or non-hydrostatic, terrain-following sigma-coordinate model designed to simulate or predict mesoscale and regional-scale atmospheric circulation. (Anthes and Warner 1978).

The Norwegian Meteorological Institute (DNMI) in a co-operation with NILU has undertaken the development and application of the weather forecast models for air pollution predictions in Norway. (Berge et. al., 2000). A detailed description of the surface and boundary conditions as well as topographical features has been of great importance for the application of the forecast system in Oslo and Bergen, Norway.

4 Measurements

Meteorological data are normally collected from a meteorological mast. The standard height for measurements in the surface boundary layer should be 10m. This is also the required measurement height for collecting wind data in the World Meteorological Organisation network.

The data to be collected are normally:

- Wind direction and speed (if possible speed at two levels),
- Temperature (dry),
- Dew point temperature (or relative humidity),
- Temperature gradient (between for instance 2 and 10 m)
- Global radiation.

In addition to these data it is recommended to measure precipitation and pressure. In addition the collection of the meteorological parameters information is needed on location, height of instruments and description of surroundings for determination of roughness-length.

Meteorological data could also be collected from the nearest airport (this can be data using the SYNOP code and performed on a routine basis by the national meteorological office). Such data normally contain information on:

Wind direction and speed, (dry) temperature, dew point temperature (or relative humidity), “description of weather”, i.e. the WW code, snow cover, cloud cover and description of types of clouds.

To evaluate and estimate the mixing height (the boundary layer height to which pollution emitted from the surface will be mixed) some information on the vertical temperature and wind variation is needed. This kind of information may be obtained from radiosonde data. Releases of radiosondes, which are instruments with sensors and radio transmitter, are performed on routine basis by the national meteorological office at 00 and 12 GMT.

Balloon soundings (radio-sonde) include measurements of pressure, temperature and dew point temperature (or relative humidity) at as many vertical positions as possible. Preferably, for each level there should be a flag indicating the significance of the level (whether the level represents a significant temperature, significant wind, or is a standard level etc.).

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About ENSIS/AirQUIS: URL: http://www.nilu.no/avd/imis/ensis-main.html