NILU : TR 4/93

NILU : TR 4/93
REFERENCE : O-92014
DATE : AUGUST 1993
ISBN : 82-425-0491-1

Air Pollution Modelling

Sources - Meteorology - Air Quality

Bjarne Sivertsen

NORSK INSTITUTT FOR LUFTFORSKNING
Norwegian Institute For Air Research
POSTBOKS 64 — N-2001 LILLESTRØM — NORWAY

Foreword

This report is a collection of lectures given at the Central Pollution Control Board in Delhi, India in 1992 as part of the "Training programme on modelling and surveillance of dispersion and movement of pollutants" undertaken for NORAD.

In addition, the following reports were presented:

Gram, F.(1992) Windfrec, Stabfrec and Metfrec. Meteorological programs - Users guide. Lillestrøm (NILU TR 4/92).

Gram, F. and Bøhler , T.(1992) Users guide for the "Kilder" dispersion modelling system. Lillestrøm (NILU TR 5/92).

Gram, F. and Bøhler, T. (1992) User's guide for the "Kilder" supporting programmes. Lillestrøm (NILU TR 6/92).

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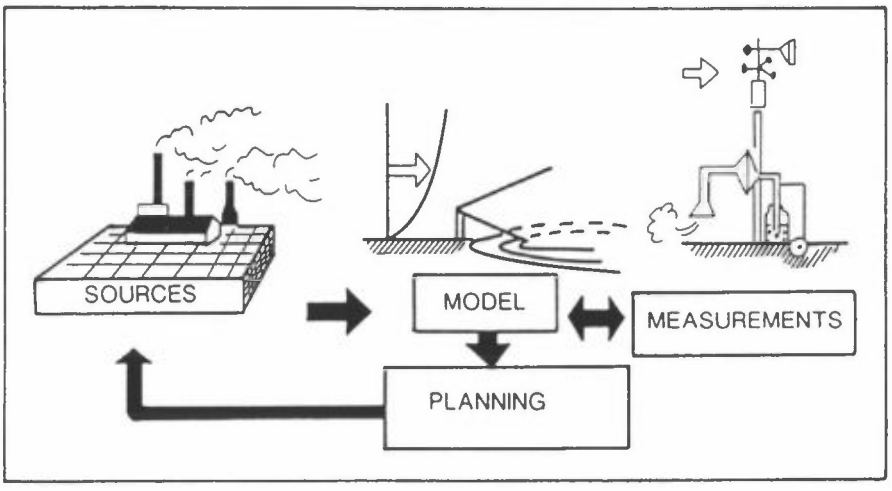

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AIR POLLUTION

1 AIR POLLUTION

What is air pollution? the Engineers' Joint Council in "Air Pollution and Its Control" gives the following definition:

"Air pollution means the presence in the outdoor atmosphere of one or more contaminants, such as dust, fumes, gas, mist, odor, smoke, or vapor in quantities, of characteristics, and of duration, such as to be injurious to human, plant, or animal life or to property, or which unreasonably interferes with the comfortable enjoyment of life and property."

This is a broad definition and one referred to frequently in writing some of the legal statutes. We might also consider the following definition of air pollution:

"Air pollution means the presence in the outdoor atmosphere of one or more air contaminants or combination thereof in such quantities and of such duration as are or may tend to be injurious to human, plant, or animal life, or property.

Air contaminants include smoke, vapors, charred paper, dust, soot, grime, carbon fumes, gases, mist, odors, particulate matter, radioactive materials, or noxious chemicals, or any other material in the outdoor atmosphere."

To become an air pollution problem three elements have to be present:

- high emissions rates,
- poor dispersion (meteorology, climatology and topography),
- adverse effects (on human health, flora, fauna or materials).

We will in this presentation discuss all these aspects and go

into some details on where do the air pollution come from, what are the sources, what are the air pollution compounds, how are they dispersed and transported in the atmosphere, what role does meteorology play and how are the affecting air quality and the environment.

The pollution of the air we breathe, ironically enough, is an indirect result of our pursuit of an even higher standard of living. Air pollution derives from the burning of fuel for heat and power, from the processing of materials, and from the disposal of wastes. Air pollution, in short, comes from those everyday acitivties which are so integral a part of this modern advanced nation.

Many of the compounds which we consider to be pollutants are minor constituents of clean air, such as, NO_2, O_3, SO_2, CO and NH_3. Though their concentrations are very low in unpolluted air, under polluted conditions they are greatly increased. For example, concentrations of 0.50 ppm for ozone, O_3, occur in the Los Angeles basin. CO levels of 20 to 50 ppm for 30 minutes are common along busy urban streets, while typical background levels are 0.1 ppm. Thus it is not the mere presence of these gases that causes problems, but it is the greatly increased concentrations that occur from man's activities.

2 SCALES

The impact of air pollution varies with the scale in space and time. Acute damage to health or vegetation might occur close to the source as a result of a short term high exposure of air pollutants. Chronic damage to nature or buildings might occur as a result of air pollution exposure over time. Various types of effects are indicated in Figure 1.

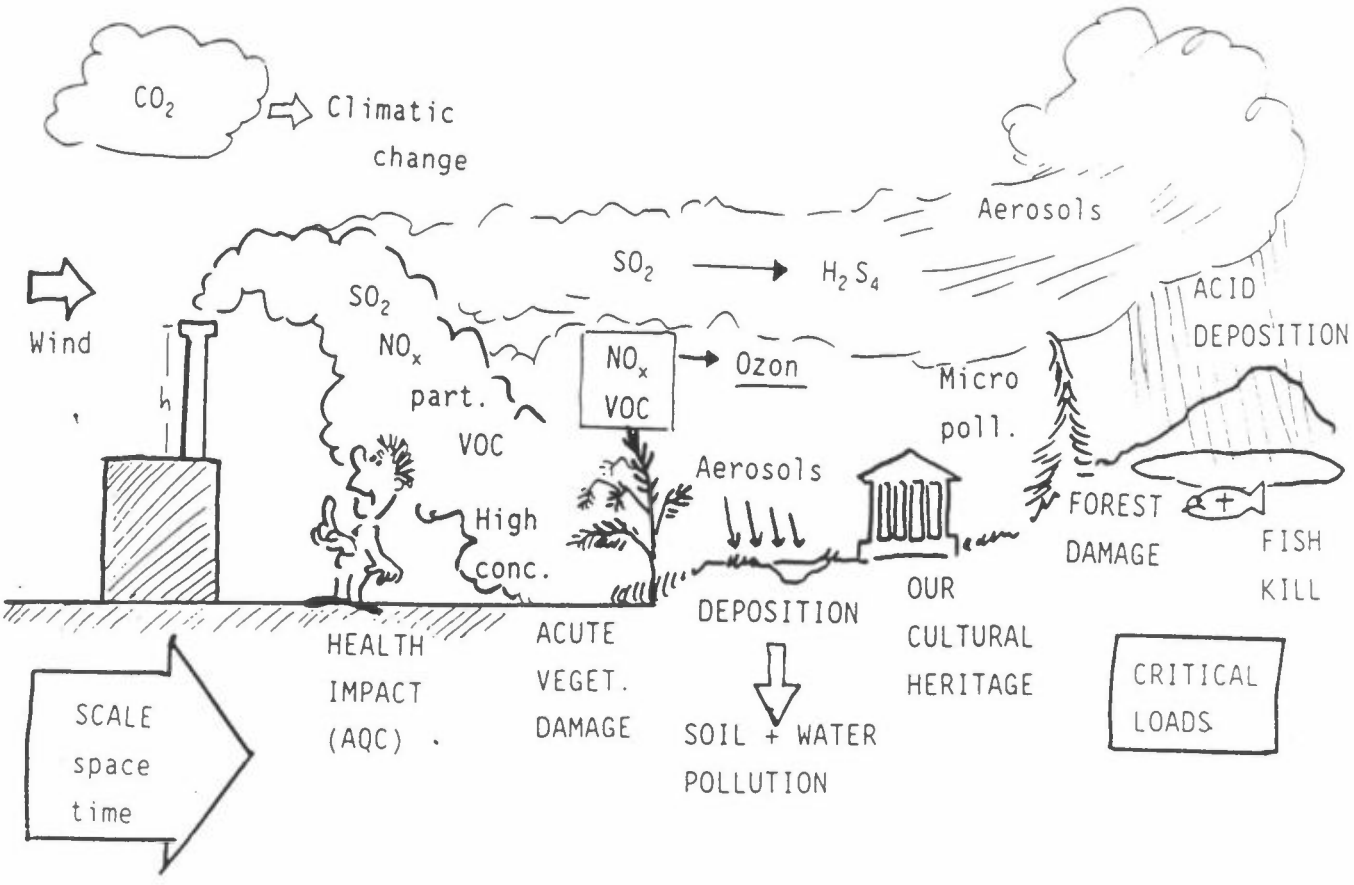

Figure 1: Environmental impact from air pollution

Typical air pollution scales, concentration ranges and effects are also given in Table 1.

Table 1: Air pollution scales.

Area	Size (km)	Conc. ($\mu g/m^3$)	Effects
Street	0.01	100-1 000	Acute, health
City blocks	0.1-1	100	Exposure, health, discomfort
Local	<10	10-100	Episodic, health, materials
Regional	100	10	Episodes, deposit. vegetation
Continental	1 000	1-10	Acid prec. forest damage
Global	10 000	<1	Climatic ch. Foodchain acc.

3 MAJOR AIR POLLUTANTS

Before we define the major air pollutants we have to know what air normally contains. The composition of clean, dry air is given in Table 2.

Table 2: Composition of clean, dry air near the sea level.

Component	Content % by volume	Content ppm	Component	Content % by volume	Content ppm
Nitrogen	78.09	780,900	Hydrogen	.00005	0.5
Oxygen	20.94	209,400	Methane	.00015	1.5
Argon	.93	9,300	Nitrogendioxide	.0000001	0.001
Carbondioxide	.0318	318	Ozone	.000002	0.02
Neon	.0018	18	Sulfurdioxide	.00000002	0.0002
Helium	.00052	5.2	Carbonmonoxide	.00001	0.1
Krypton	.0001	1	Ammonia	.000001	.01
Xenon	.000008	0.08			
Nitrousoxide	.000025	0.25			

Note: The concentrations of some of these cases may differ with time and place, and the data for some ar open to question. Single values for concentrations, instead of ranges of concentrations, are given above to indicate order of magnitude, not specific and universally accepted concentrations.

Note that many of the compounds which we consider to be air pollutants are minor constituents of clean air, such as NO_2, O_3, SO_2, CO and NH_3. In clean air the concentrations are very low. Under polluted conditions their concentrations increase by factors of 10-100.

The sources of air pollutants which might enter into the "clean air" might origin from:

- burning of fossil fuels (coal, oil, gas) in stationary and mobile sources.
- industrial processes

- waste incineration
- blow up and resuspension of soil and road dust
- forest fires and accidental burning
- diffusive leakages from treating of hydrocarbons
- use of sprayboxes, cooling agents and fire extension tools.

A list of air pollution components, sources, typical concentration ranges in the atmosphere and potential effects are presented in Table 3.

Table 3: Major air pollutants

	Sources	Typical conc.*)	Effects
SO_2	oil, coal, diesel cars, industry	5-1000 ($\mu g/m^3$)	Health Acid rain Corrosion
NO_x	fossil fuel, automobiles, industry	10-1000 ($\mu g/m^3$ (NO_2))	Health Acid rain
CO	cars, industry, wood burning	1-50 (mg/m^3	Health
TSP	road dust, burning	10-500 ($\mu g/m^3$)	Health Well being
Soot	waste inc., fossil fuel, industry	5-300 ($\mu g/m^3$)	Health
VOC	petrochem. proc., oil, gas, incineration	1-100 ppb (C_2-C_5/(HC)	Health
CFC	insolation, spray, cooling	0.2-0.4 (ppb)	Ozone layer
Ozone (trop.)	VOC + NO_x	10-300 ($\mu g/m^3$	Health Forests Materials
CO_2	fossil fuel	300-400 (ppm)	Climatic change
Ozone layer	CFC, N_2O, CH_4, halones		Ozone red. Skin cancer

*) Range from country side to urban

The typical levels of air pollutants strongly vary from the stack or emission source to the different type of environments; street canyons, urban air, background areas as shown in Table 4.

Table 4: Typical concentrations of pollutants in samples of ambient air.

Pollutant	Background	Urban ambient air	Stack effluents	Auto emission
CO	0.1 ppm	5-10 ppm	2000-10.000 ppm	1-4%
SO_2	0.2 ppb	0.02-2 ppm	500-3500 ppm	50-100 ppm
NO_x	0.2-5 ppb	0.2-1.0 ppm	1500-2500 ppm	1500 ppm
O_3	10 ppb	0.1-0.5 ppm	-	-
Suspended particulates	10 $\mu g/m^3$	60 $\mu g/m^3$	$35 \cdot 10^6$ $\mu g/m^3$	
Methane	1.5 ppm	1-10 ppm		
Other hydrocarbons	< ppb	1-100 ppb		1000 ppm

In the following lectures we will mainly deal with local air pollution problems. If we consider the air quality model as a basic working tool, we will be discussing:

- emissions and emission inventories
- meteorology and climate, turbulence and dispersion
- air quality; levels, indicators, guidelines, measurements
- models; types, parameters, applications
- air quality surveillance and planning

Figure 2 shows the model as an important tool in the decision making process.

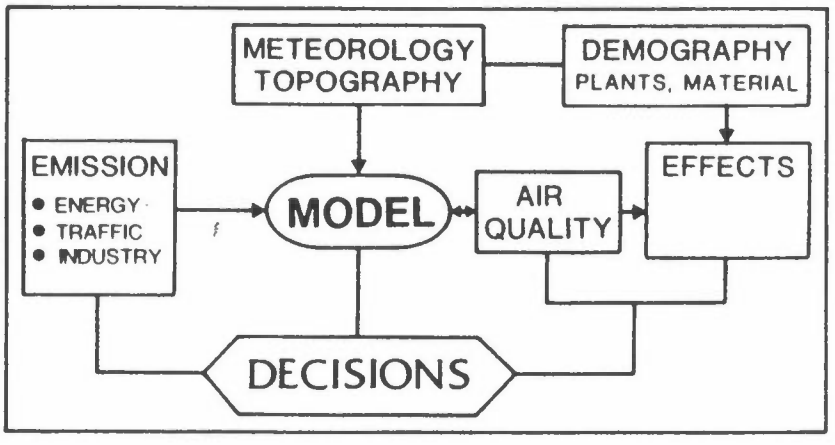

Figure 2: The air quality model as an important tool in decision making.

The modelling concept has been used in:

- urban air pollution planning
- industrial impact assessment
- traffic air pollution studies
- site studies
- air pollution forecast, etc.

This picture of the input and output data in air pollution modelling should be kept in mind when we continue this series of lectures.

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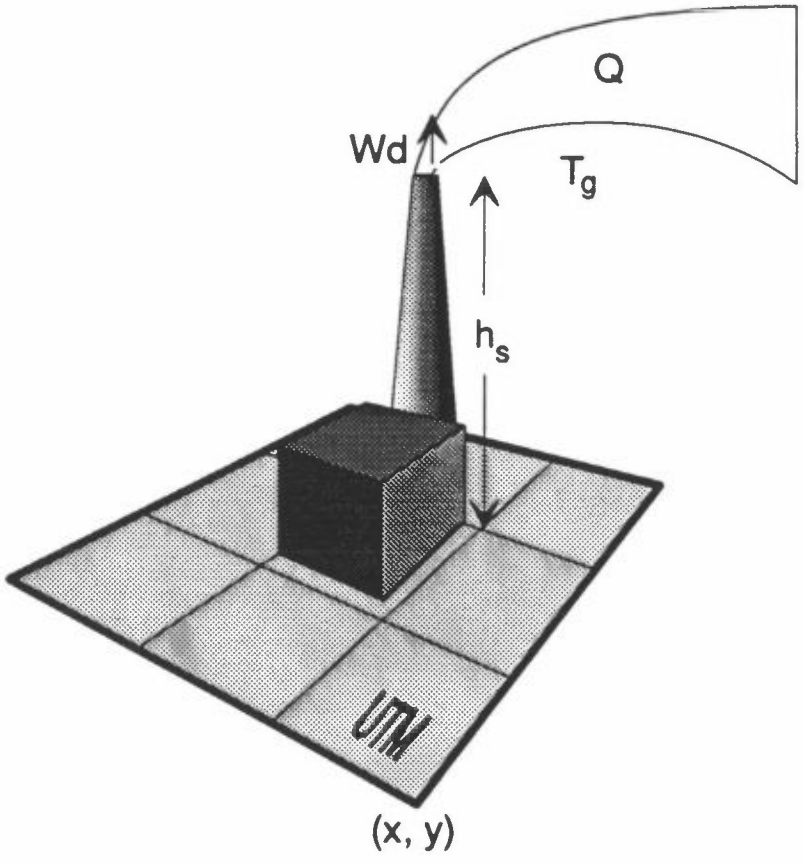
Emissions of Air Pollution

B. Sivertsen



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EMISSIONS OF AIR POLLUTION

1 EMISSION GENERATION PROCESSES

Atmospheric emissions arise from certain physico-chemical and biological processes.

Such processes occur within sources related to socio-economic activities, for example: combustion of fuel oil (process) in boilers of a certain size and type (source) to generate heat for district heating (activity).

The emissions of air pollutants are usually given by source category or by specific air pollution compounds. Relevant source categories for 6 different air pollutants are given in Table 1.

Table 1: Sources of SO_x, NO_x, VOCs, CH_4, NH_3 and CO.

Source category[a]	SO_x	NO_x	NMVOCs	CH_4	NH_3	CO
1. Power generation and district heating	XX	XX	X	X		X
2. Commercial, institutional and residential combustion plants	X	X	X	X		XX
3. Industrial combustion plants and processes with combustion	XX	XX	X	X		X
4. Non-combustion processes	X	X	XX	X	X	(XX)
5. Extraction and distribution of fossil fuels	X	X	X	XX		X
6. Solvent use			XX			
7. Road transport	X	XX	XX	X		XX
8. Other transport	X	(XX)	X	X		X
9. Waste treatment and disposal	X	X	X	XX	X	X
10. Agriculture			X	XX	XX	
11. Nature			(XX)	X		

a) Relevant sources are given by "X" and major source cateories are presented by "XX".
The parentheses indicate that the given source category may be a major one for some countries.

Looking at the US emissions for 1969 (Table 2) transportation at that time was the major source for CO, HC and NO_x while fuel combustion in stationary sources were the major sources for SO_x. Particulates originated from industrial processes.

Table 2: US air pollution emissions for different source categories (1969) (10^6 tons/y).

Source category	Type					
	Total	Carbon monoxide	Hydro-carbons	Nitrogen oxides	Sulfur oxides	Particu-lates
Total for 1969	281.2	151.4	37.4	23.8	33.4	35.2
Transportation	144.4	111.5	19.8	11.2	1.1	0.8
Fuel combustion (stationary)	44.3	1.8	0.9	10.0	24.4	7.2
Industrial processes	39.6	12.0	5.5	0.2	7.5	14.4
Refuse disposal	11.9	7.9	2.0	0.4	0.2	1.4
Miscellaneous	41.0	18.2	9.2	2.0	0.2	11.4

Industrial sources represent a variety of emissions dependent upon processes, content of raw materials, use of fuels and air pollution. Table 3 indicates some sources of industrial air pollution.

Table 3: Sources of industrial air pollution.

Industry	Aerosols	Gases and vapors	Typical loss rates
Combustion	Dust, fumes	NO_2, SO_2, CO, organics, acids	0.05-1.5% by weight of fuel
Petroleum	Dust, mist	SO_2, H_2S, NH_3, CO, hydrocarbons, mercaptans	0.25-1.5% by weight of material processed
Chemical processes	Dust, mist fume, spray	Process-dependent	0.5-2% by weight of material processed
Pyro- and electro-metallurgical processing	Dust, fume	SO_2, CO, fluorides, organics	0.5-2% by weight of material processed
Mineral processing	Dust, fume	Process-dependent	1.3% by weight of material processed
Food and feed processing	Dust, mist	Odorous materials	0.25-1% by weight of material processed

2 EMISSION ESTIMATES

The fundamental equation to perform emission estimates is the following:

activity rate x emission factor = emission rate

where:

- activity rate relates the amount of fuel used or material produced to the period of time covered and is given e.g. in tonnes or product per year,
- emission factor indicates the amount of pollutant released per unit of activity rate and is given e.g. in kilogrammes of pollutant per tonne of product, and
- emission rate specifies the amount of pollutant generated per unit of time and is given e.g. in kilogrammes of pollutant per year.

In calculating emission levels, the spatial coverage may relate to:

- point, area, and line sources,
- administrative units at different territorial levels, and
- the whole country,

according to the background data used.

In nation-wide inventorying, two types of emission inventories can be distinguished:

- national total inventories without any spatial resolution, and
- national spatial inventories on a certain grid system or relating to administrative units of a certain territorial level.

Depending on the circumstances, sources can be treated individually or collectively:

- the individual approach as a source-by-source approach relates to point sources such as power plants, refineries, and airports for which site-specific activity, and if possible, emission data can be recorded, and

- the collective approach predominantly relates to sources comprising large numbers of small emitters, for example all industrial boilers or those of a certain size, are treated as a whole.

Depending on the aims of the inventory and on resources available, analysts must decide to what extent the individual approach is to be applied. Major advantage of this type of procedure will be an essential enlargement of information about spatial distribution concerning both location and amount of emission.

2.1 STATIONARY POINT SOURCES

Activity data should be linked to the emission generation process as closely as possible. Two examples can be given:

- for emission from power plant combustion of certain fuels: (1) fuel input instead of electricity output should be used, and (2) energy units instead of mass units should be used. Consequently, determination of appropriate heat values of fuels may be necessary where fuel data are available in mass units only;

- for combustion related emissions in general: emission characteristics vary fuel by fuel and hence activities should be reported in this way, instead of using a total energy approach.

One must pay special attention where both combustion and fuels and processing of materials may have effects on emissions. Fuel mixture as well as specific energy demands may change over time. As a consequence, both sides need to be taken into account: fuel input as well as product output.

Whenever point sources are estimated individually, the sum of the activity represented by these sources should be subtracted rom the collective activity estimate. This is to avoid double-counting the individually considered point sources when estimating the rest of the source activity emissions (the collective approach).

As in the case of point sources treated individually in the accounting for processes with combustion, attention should be paid to avoid double-counting of energy consumption statistics. Reference activity data may be available from public and private statistics, institutions or research projects. Information of fuels should include non-commercial fuels and wastes used for energy generation.

2.1.1 Emission factors from literature

In most cases emission factors from literature are not clearly described. Consequently, the user should thoroughly check whether the conditions under which such factors have been established are well understood. The following questions can be addressed:

- What range of boiler size is represented?
- Is refinery throughput referred to in terms of crude oil or total oil?
- Do refinery sources include gasoline dispatch or not?
- Regarding process with combustion referred to in terms of material, are combustion related emissions included or not?
- Is the emission factor controlled or uncontrolled?

In deciding whether to use emission factors from an outside reference for a given country, one must check whether comparable conditions exist, e.g. regarding raw material characteristics, type of process, or operating conditions. Application of per capita coefficients cannot be recommended because such parameters reflect very specific socio-economic conditions.

As an example the estimate of SO_2-emissions using available emission factors is dependent upon several conditions. Parameters influencing the SO_x-emission factors might be:

- sulphur content of the fuel,
- sulphur retention in ashes,
- control efficiency, free gas desulphurization,
- type of processes.

Examples of emission rates of SO_2 from various processes are approximately as follows:

Burning of coal : lb SO_2/ton = 38 x per cent sulfur by weight.

Burning of fuel oil : lb SO_2/1000 gal = 159 x per cent sulfur by weight.

Diesel engine exhaust : lb SO_2/1000 gal = 40, based on 0.3% S in oil.

Sulfuric acid manufacture: 20-70 lb SO_2/ton of 100% acid.

Copper smelting[b] : 1250 lb SO_2/ton of concentrated ore.

Zinc smelting[b] : 530 lb SO_2/ton of concentrated ore.

Sulfite paper making : 40 lb SO_2/ton of air-dried pulp.[a]

Coke drying : 0.25 lb SO_2 plus SO_3/ton of product.

a A small amount of this tonnage is converted to sulfuric before discharge to acid mist the atmosphere.

b these are for primary smelting processes.

c Assumes 90% recovery of SO_2.

Emission rates from a medium sized power plant boiler are given in Table 4.

Table 4: Typical emission rates from medium sized power plants using coal, fuel oil or gas.

Pollutant	Em.rate	Coal	Oil	Gas
SO_2	mg S/MJ	~400	240	<1
NO_x	mg NO_2/MJ	250	170	60
Particles	mg/MJ	10*)	5	<1
As	µg/MJ	1.5	0.4	-
Cd	µg/MJ	0.1	0.2	<0.04
Hg	µg/MJ	1.0	0.06	<0.004
V	µg/MJ	7	260	<0.0003
CO_2	g/MJ	110	85	57

*) 1 kg coal ~30 MJ (1.6% S in coal)

Typical emission factors for particulate emissions from different sources are given in Table 5.

Table 5: Typical rates of particulate emission.

Emission Factors for Selected Categories of Uncontrolled Sources

Emission source	Emission factor
Natural gas combustion	
Power plants	15 lb/million ft^3 of gas burned
Industrial boilers	18 lb/million ft^3 of gas burned
Domestic and commercial furnaces	19 lb/million ft^3 of gas burned
Distillate oil combustion	
Industrial and commercial furnaces	15 lb/thousand gallons of oil burned
Domestic furnaces	8 lb/thousand gallons of oil burned
Residual oil combustion	
Power plants	10 lb/thousand gallons of oil burned
Industrial and commercial furnaces	23 lb/thousand gallons of oil burned
Coal combustion	
Cyclone furnaces	2X (ash percent) lb/ton of coal burned
Other pulverized coal-fired furnaces	13-17X (ash percent) lb/ton of coal burned
Spreader stokers	13X (ash percent) lb/ton of coal burned
Other stokers	2-5X (ash percent) lb/ton of coal burned
Incineration	
Municipal incinerator (multiple chamber)	17 lb/ton of refuse burned
Commercial incinerator (multiple chamber)	3 lb/ton of refuse burned
Commercial incinerator (single chamber)	10 lb/ton of refuse burned
Flue-fed incinerator	28 lb/ton of refuse burned
Domestic incinerator (gas-fired)	15 lb/ton of refuse burned
Open burning of municipal refuse	16 lb/ton of refuse burned
Motor vehicles	
Gasoline-powered engines	12 lb/thousand gallons of gasoline burned
Diesel-powered engines	110 lb/thousand gallons of diesel fuel burned
Gray iron cupola furnaces	17.4 lb/ton of metal charged
Cement manufacturing	38 lb/barrel of cement produced
Kraft pulp mills	
Smelt tank	20 lb/ton of dried pulp produced
Lime kiln	94 lb/ton of dried pulp produced
Recovery furnaces[a]	150 lb/ton of dried pulp produced
Sulfuric acid manufacturing	0.3-7.5 lb acid mist/ton of acid produced
Steel manufacturing	
Open-hearth furnaces	1.5-20 lb/ton of steel produced
Electric-arc furnaces	15 lb/ton of metal charged
Aircraft, 4-engine jet	7.4 lb/flight
Food and agricultural	
Coffee roasting, direct-fired	7.6 lb/ton of green coffee beans
Cotton ginning and incineration of trash	11.7 lb/bale of cotton
Feed and grain mills	6 lb/ton of product
Secondary metal industry	
Aluminum smelting, chlorination-lancing	1 000 lb/ton of chlorine
Brass and bronze smelting, reverberatory furnace	26.3 lb/ton of metal charged

[a]With primary stack gas scrubber.

Sources: *Air Quality Criteria for Particulate Matter*, AP-49, National Air Pollution Control Administration, January 1969; and *Control Techniques for Particulate Air Pollutants*, AP-51, National Air Pollution Control Administration, January 1969.

2.2 MOBILE SOURCES (THE AUTOMOBILE)

The unconctrolled engine emits different amounts of pollutant depending on the driving mode. At idle large amounts of CO are emitted and upon acceleration large amounts of NO_x. Table 6 gives and indication of the typical exhaust gas emission for an uncontrolled engine.

Table 6: Typical exhaust gas compositions.

Mode of operation	Unburned hydrocarbons ppm	Carbon monoxide vol. percent	Nitrogen oxides ppm	Hydrogen vol. percent	Carbon dioxide vol. percent	Water vol. percent
Idle	750	5.2	30	1.7	9.5	13.0
Cruise	300	0.8	1500	0.2	12.5	13.1
Acceleration	400	5.2	3000	1.2	10.2	13.2
Deceleration	4000	4.2	60	1.7	9.5	13.0

* Note results taken with a flame ionization detector (FID) are about 80 percent higher.

However the engine is not the only source of pollution. Figure 1 shows emission from different sources on a car. The fuel systems emission comes from the fuel tank and the carburetor and consists exclusively of hydrocarbons. Crankcase emission, also HC, comes mainly from the gas-air mixture which blows by the piston rings. Exhaust gas contains CO, NO_x, and additional HC as well as the lead compounds emitted.

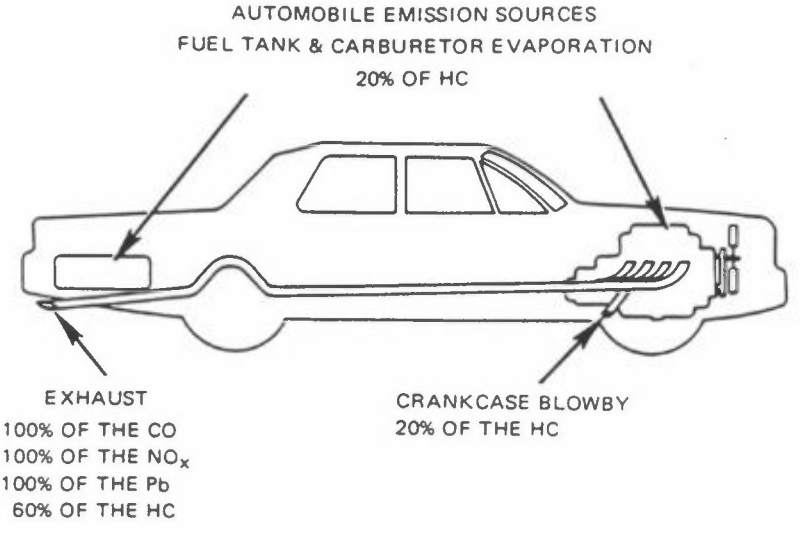

Figure 1: Approximate distribution of automobile emission by source

Figure 2 shows CO and No_x emissions as a function of vehicle speed, for light duty gasoline and heavy duty diesel vehicles, for horisontal roads.

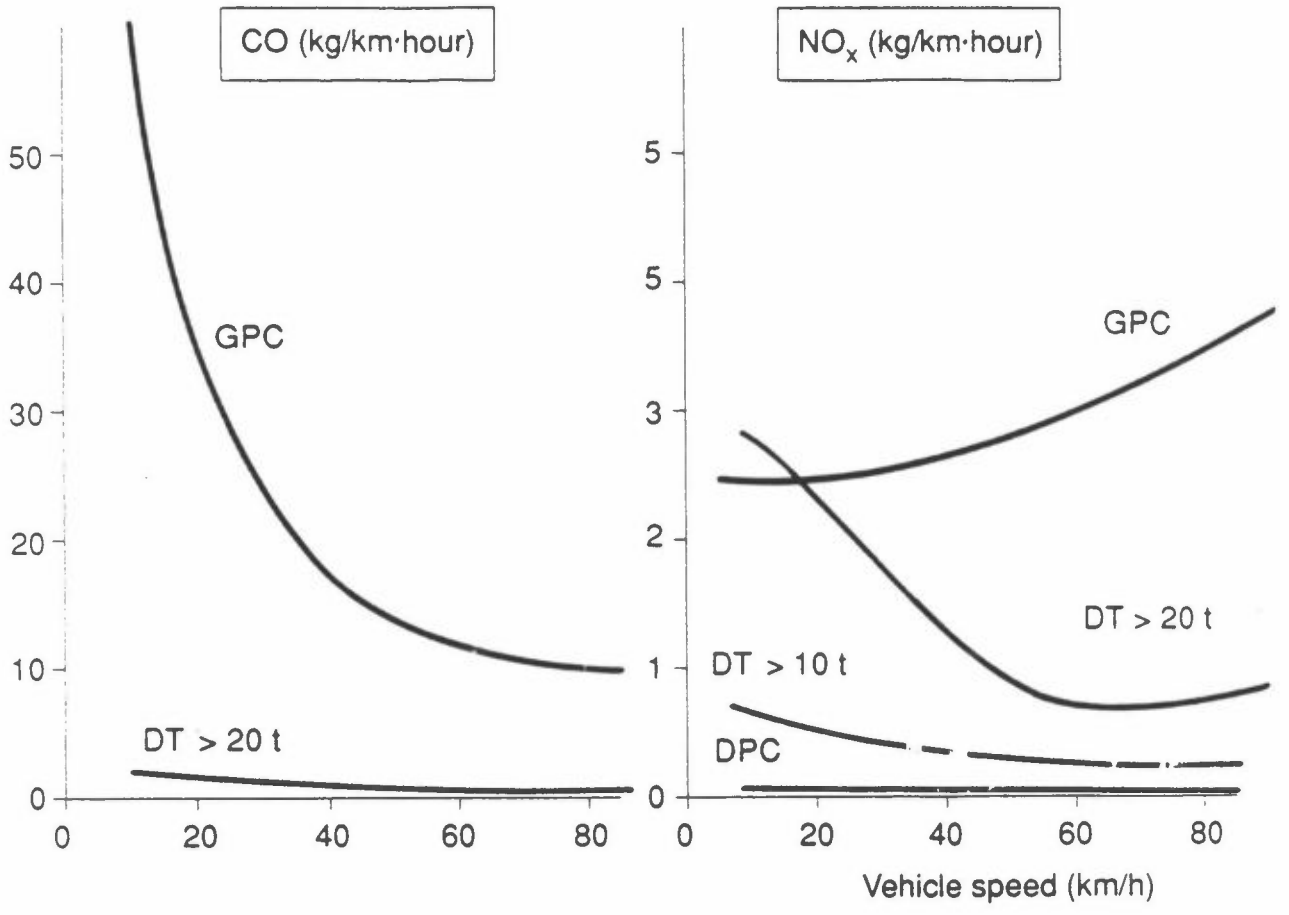

Figure 2: Emissions of CO and NO_x as a function of vehicle category.

The emissions are calculated per km road per hour, for 1 000 cars/hour, for the following composition:
85% gasoline passenger cars (GPC)
5% diesel passenger cars (DPC)
5% diesel trucks, <10 tonnes (DT, <10t)
5% diesel trucks, >20 tonnes (DT, >20t)

Figure 3 shows that velocity turbulence (accellerations) increase emissions considerable.

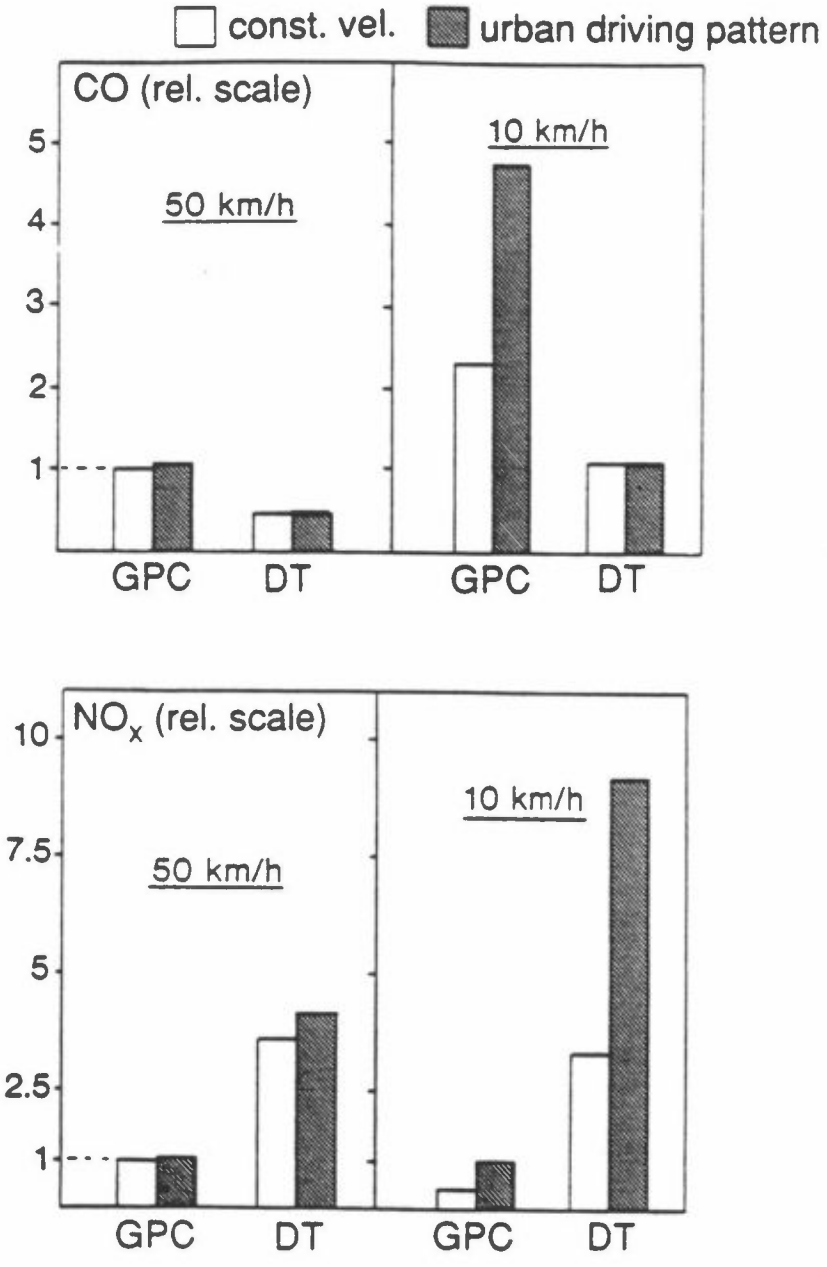

Figure 3: Example of CO and NO_x emissions (relative scale) for gasoline passenger cars (GPC) and diesel trucks (DT), for constant velocity and for typical urban driving patterns.

A summary of emission factors used in Norway is presented in Table 7.

Table 7: Emmission factors and chemical composition of particles, for main constituents of car exhaust.

	Gasoline passengers cars		Diesel vehicles	
	Leaded gasoline 0.15 g Pb/l	Nonleaded gas/ 3-way catalyst	Light duty <3.5 t	Heavy duty >3.5 t
Emission factors				
Exhaust particles mg/km	20-40	5	450	1 300
Lead mg/km	2-3			
PAH µg/km	100-400	5-10	750	2 500
mg/kg	1.5-5	0.05-0.1	8	8
Mutagenicity				
10^3 rev/km	20-100	2.5	300	500-1 000
10^3 rev/kg	250-1 200	25-60	3 000	1 500-3 000
Chemical composition %				
Inorganic carbon	40	5-20	50-80	
Organic carbon		15-35	15-30	
Lead	10			
SO_4		30-50	1-5	

From traffic investigations performed in Delhi in 1982 it was found that 65% of private owned vehicles were two-wheelers, 22% private cars and only 8,5% huses and goods vehicles. Emission factors were estimated from measurements at two grid areas in Delhi. The emission factors are shown in Table 8.

Table 8: Emission factors in kg of pollutant for vehicle. Kilometre x 10^3.

Type of vehicle	Particulates	Sulphurdioxide SO_2	Nitrogen oxide NO_2	Hydrocarbons HC	Carbon monoxide CO
Light duty, gasoline powered	0.33	0.08	3.2	6.0	40
Light duty, diesel powered	0.45	0.39	0.99	0.28	1.1
Heavy duty, diesel powered	0.75	1.5	21.0	2.1	12.7
Motor cycles	0.2	0.02	0.07	10	17 *

*It was taken as 21.25 in place of 17 to accommodate higher quantity of CO emission from 3-wheelers, as the petrol consumption for the 3-wheelers is one and a half times that of 2-wheeler (motor cycle or scooter), per km travel. Thus 17 for 2-wheeler and 25.5 for 3-wheeler and for LTV as a group 1/2(17 + 25.5) = 21.25.

3 EMMISSION INVENTORIES

Air pollution emission inventories for selected pollutants have to be established for the area. The emission inventory yields a specific year of reference, supplemented by additional statistical data, if available.

For assessment programmes the emission inventory is usually established for atmospheric dispersion modelling purposes.

The emission inventories are thus generally composed of three categories of emitters: point sources (stationary), mobile sources (line sources) and area sources (see Figure 4). A large fraction of the total emissions usually come from point and line sources.

A distinction must be made between the principal air pollutants of concern. These are usually sulphur dioxide (SO_2), oxides of nitrogen (NO_x), carbon monoxide (CO), hydrocarbons (HC) and particulates.

Important air pollutants are also formed in the atmosphere from the emissions of No_x, HC, SO_2, Cl and others.

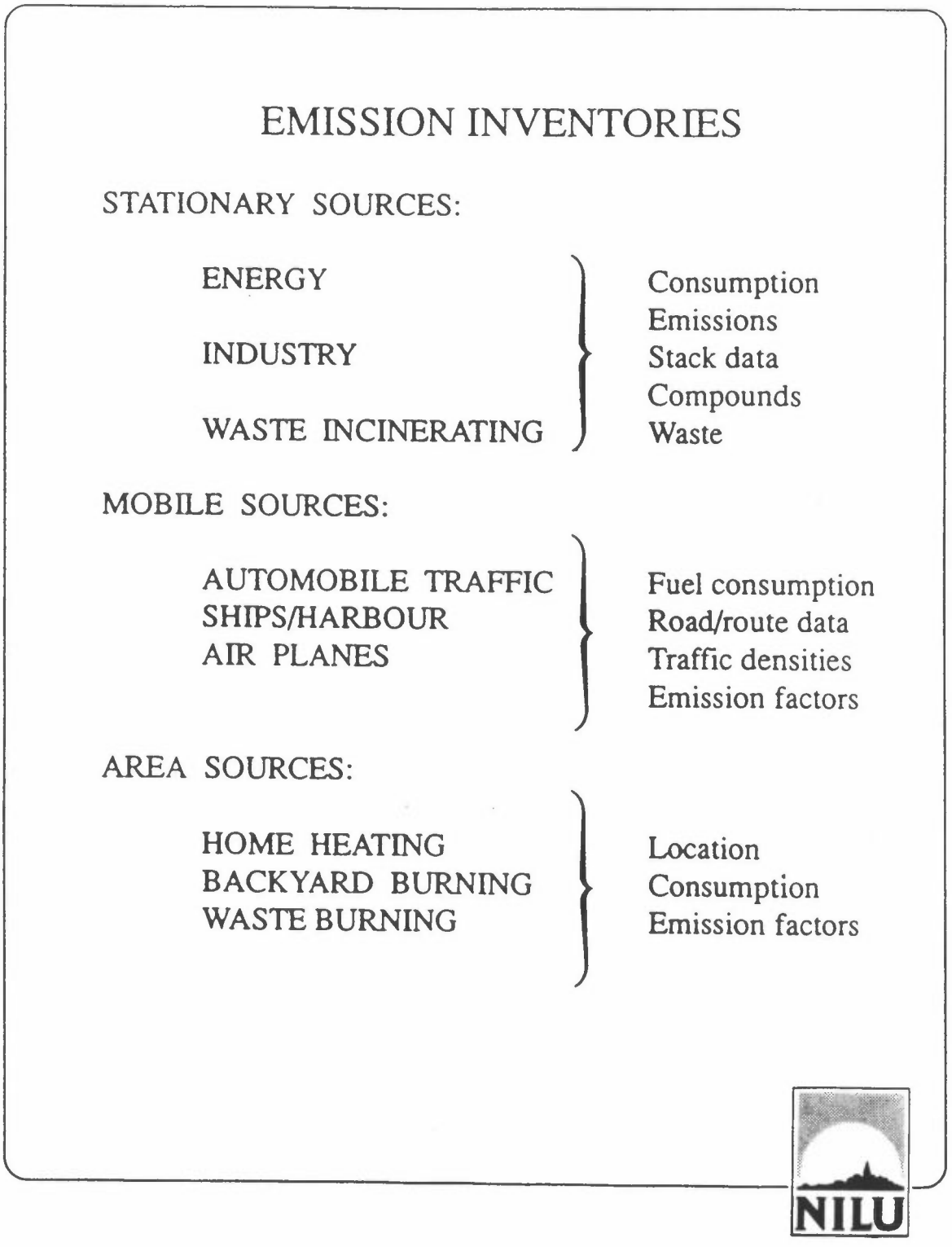

Figure 4: Emission inventories

Specific hazardous pollutants (e.g. asbestos, fluorides, vinyl chloride) are important in land use planning and emission inventories for such spoecies are important to obtain.

The emission inventory should be divided into source categories:

- household and small consumers
  based upon energy consumption, use of fuel oils, type of heating, population distribution, density of dwellings, emission factors, etc.

- transport
  based upon: number of motor vehicles, traffic pattern, driving conditions, emission factors for different type of vehicles, (passenger, cars, trucks, buses..) variation in traffic density with time. (Figure 5).

- industry based upon: emission measurements, fuel consumption, type of processes, production rate, time variation. (Figure 6).

- electricity generation (power plant)
  based upon: fuel consumption, fuel type and emission factors.

- incineration
  based upon: type of furnace, emission control system, emission measurements.

- miscellaneous.

The emission factors are essential when making an emission inventory, because they express the relationship between fuel consumption and the actual release rate for emissions from a specific source category.

TRAFFIC EMISSIONS

- △ Road coordinates
- △ Traffic density data
- △ Heavy duty traffic ratio
- △ Driving speeds
- △ Road width
- △ Open roads, "fasade"

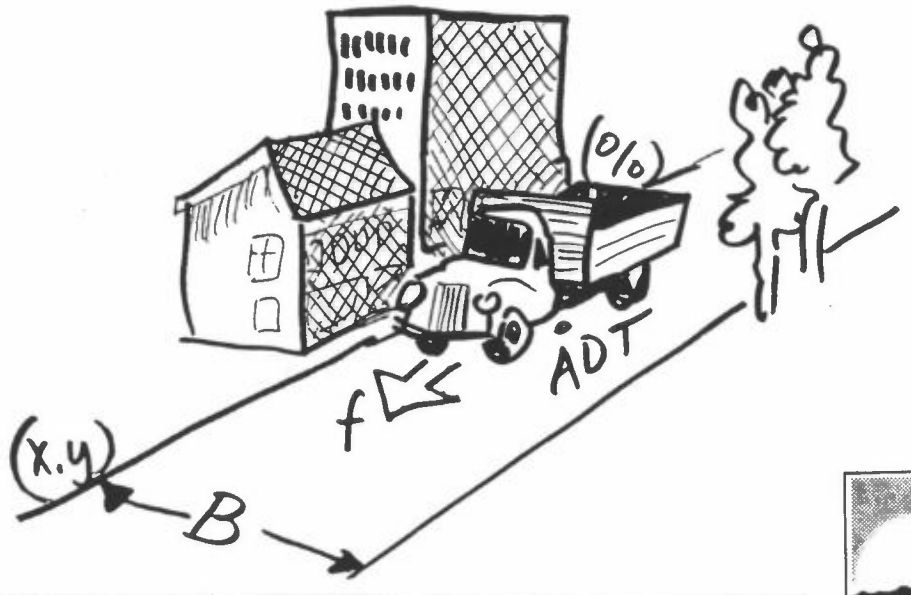

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Figure 5: Traffic emissions

INDUSTRIAL, POINT SOURCES

- position (UTM coordinates)
- release, stack heights
- exit gas velocities
- exit gas temperature
- stack diameter
- building dimensions
- release rates (kg/h or g/s)

  SO_2, NO_x etc.

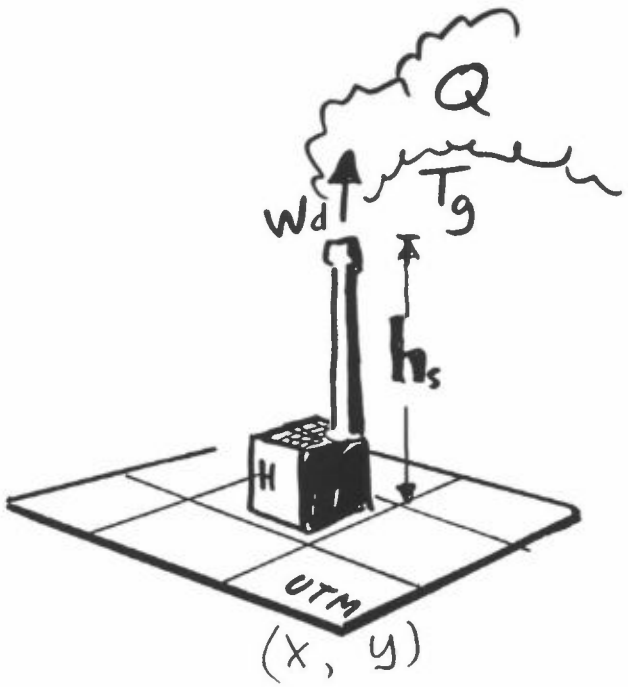

Figure 6: Industrial point sources

The emission inventory data also has to include information about stack heights, gas flow rates, and exit gas temperature.

The details required in an emission inventory is based upon the purpose of the study. The source categories are often specified on a 1 km x 1 km grid. the location of large point sources should be specified more precisely. Emission factors typically apply to domestic heating sources, traffic using petrol or oil and in some cases to other air polluting activities.

When an emission inventory has been fulfilled gridded information should be available. On a local scale these data should represent adequate input to the air pollution models.

Examples of such information presented in a 1 km x 1 km grid is shown in Figure 8. On a national scale emission inventories have been used to estimate trends in the development of air pollution. Figure 8 show trends in national emissions in the UK, Federal Republic of Germany and the USA.

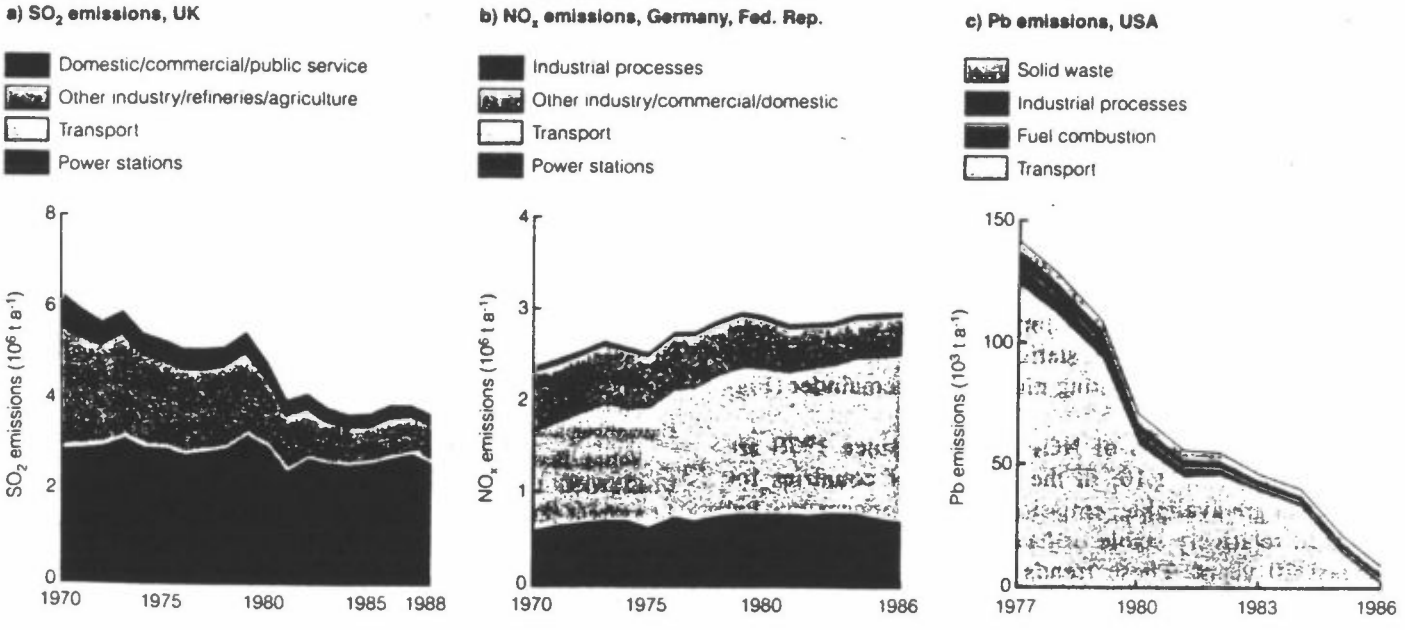

Figure 7: Trends in national emissions of a) SO_2 in the UK, b) NO_x in Germany, Fed. rep., and c) Pb in the USA. Sources: Munday, 1989; Umweltbundesamt, 1989; EPA, 1988.

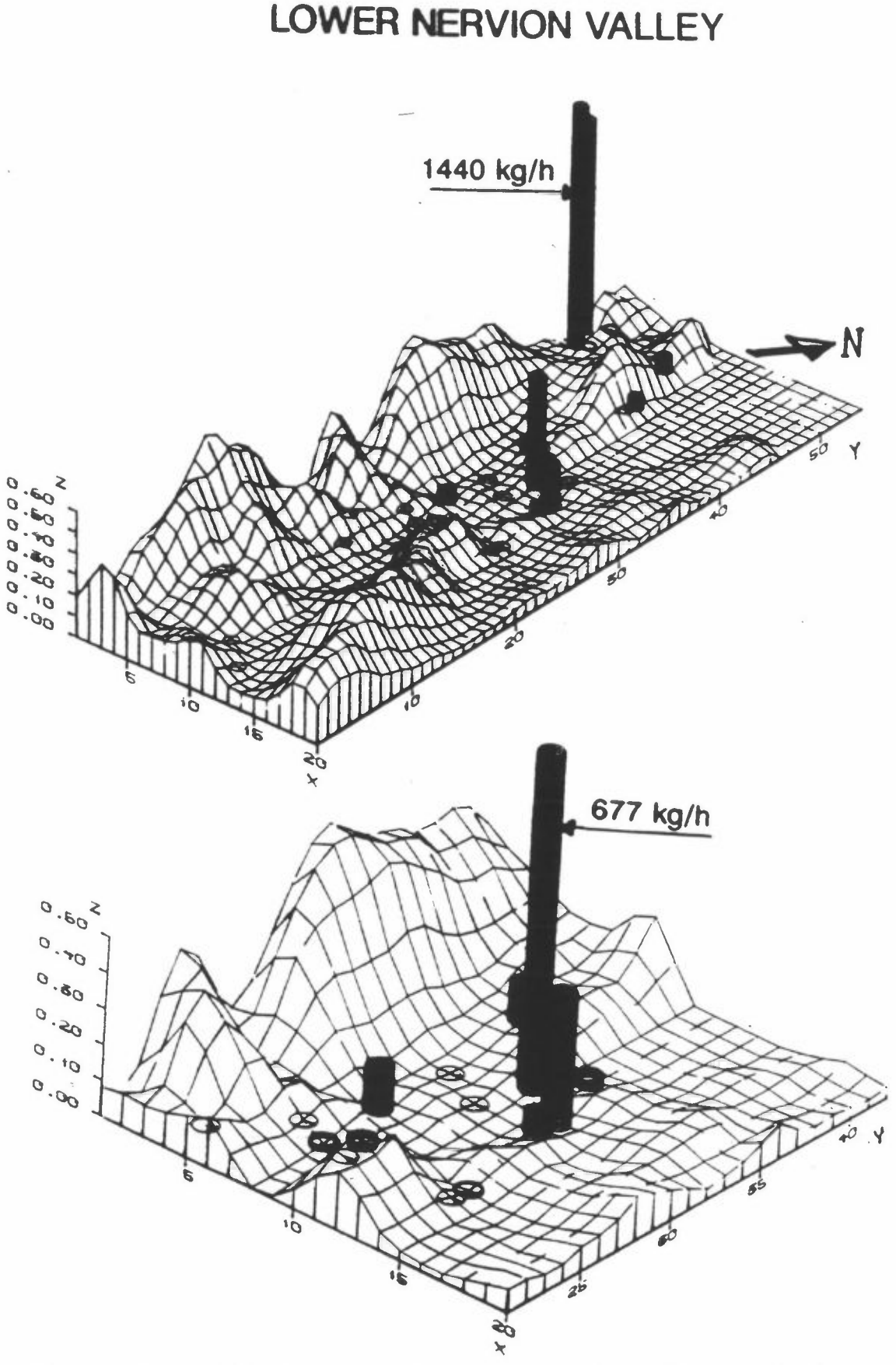

Figure 8: Gridded emission data for SO_2 emissions in a 1 km x 1 km grid for the Bilbao area in Spain.

On an international scale NILU has been undertaking efforts to develope an Emission Inventory for Europe. Guidelines for harmonization of emission estimates have been issued.

Comparability of national emission inventories is a major international challenge whenever estimations are performed by individual countries independently. Systematic efforts are necessary to provide a sufficient degree of comparability and, under practical conditions, a stepwise approach is probably the best.

The features of collaboration procedures among countries which will have to be established can be characterized by three essential elements:

i) A spirit of co-operation.
ii) Rigorous application of common definitions for estimating and reporting emissions.
iii) Co-ordinated verification procedures.

In practice however, one has to deal with diverse conditions, for example:

- background data for emission estimates frequently vary in type, the degree of details, and quality depending on national circumstances,
- in certain cases background data are not available at all,
- institutions vary in experience with the subject, and
- sufficient resources may not always be available.

As a consequence, gaps have to be closed and difficulties overcome. Progress should be sought as much as possible from an exchange of information and continuing research.

Figure 9 shows an example of emission of sulphate in Europe.

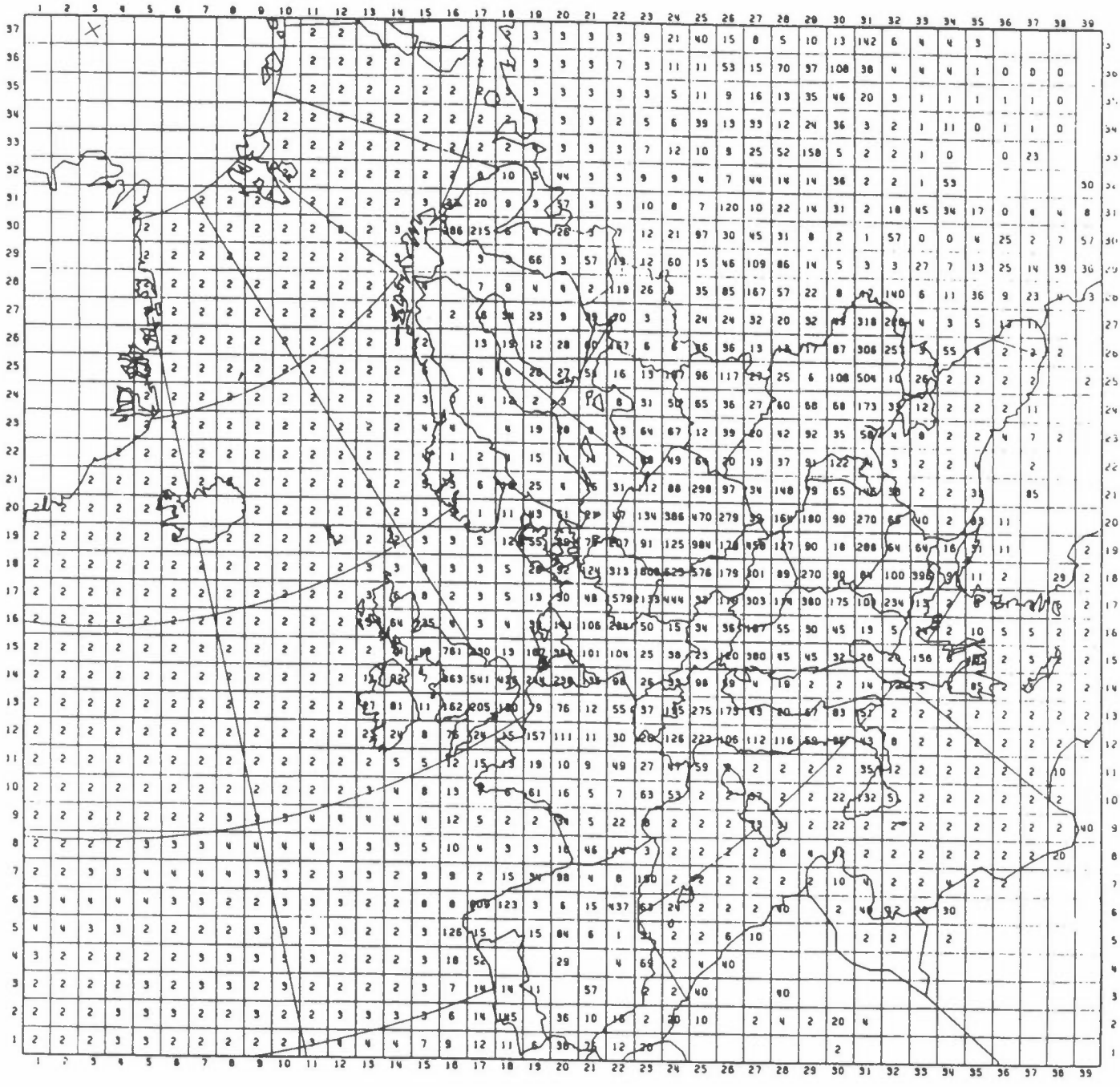

Figure 9: 1989 - emissions of sulphur dioxide in each grid square of the EMEP/MSC-W grid for calculations.
Unit: 1000 tonnes per annum as SO_2.

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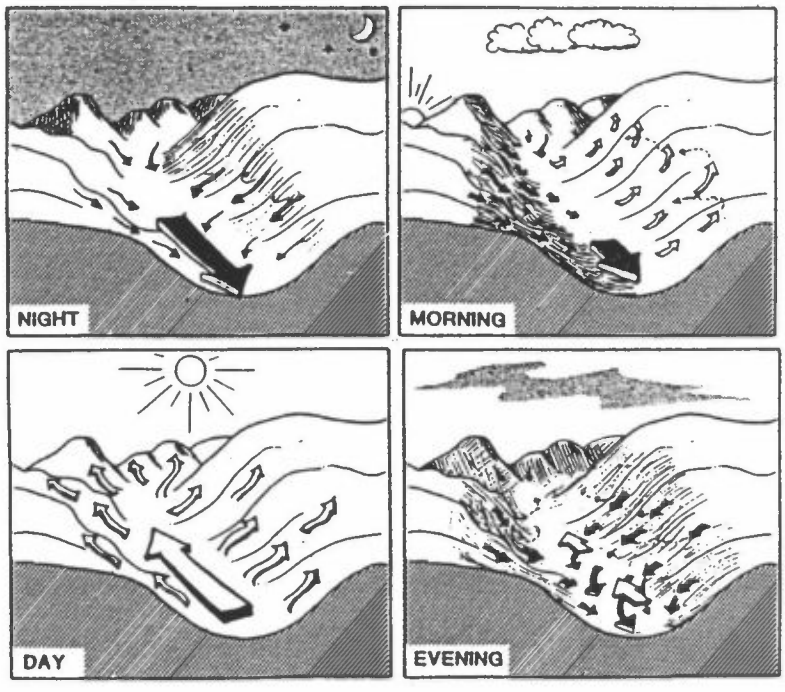
REFERENCE : O-92014
DATE : MAY 1992

Meteorology

B. Sivertsen



NILU

NORSK INSTITUTT FOR LUFTFORSKNING
Norwegian Institute For Air Research
POSTBOKS 64 — N-2001 LILLESTRØM — NORWAY

METEOROLOGY

1 INTRODUCTION

Meteorology specifies what happens to a puff or plume of pollutant from the time it is emitted to the time it is detected at some other location. The motion of the air causes a dilution of the air pollutant and we would like to be able to calculate how much dilution occurs as a function of the meteorology or atmospheric conditions. To put it another way, given a known emission we would like to calculate the resulting concentrations downwind of the source. To do this will require some knowledge of the elements of meteorology.

The weather on all scales in space and time acts on the transport and dilution of air pollutants and plays different roles in producing the air quality that we measure and feel (Figure 1).

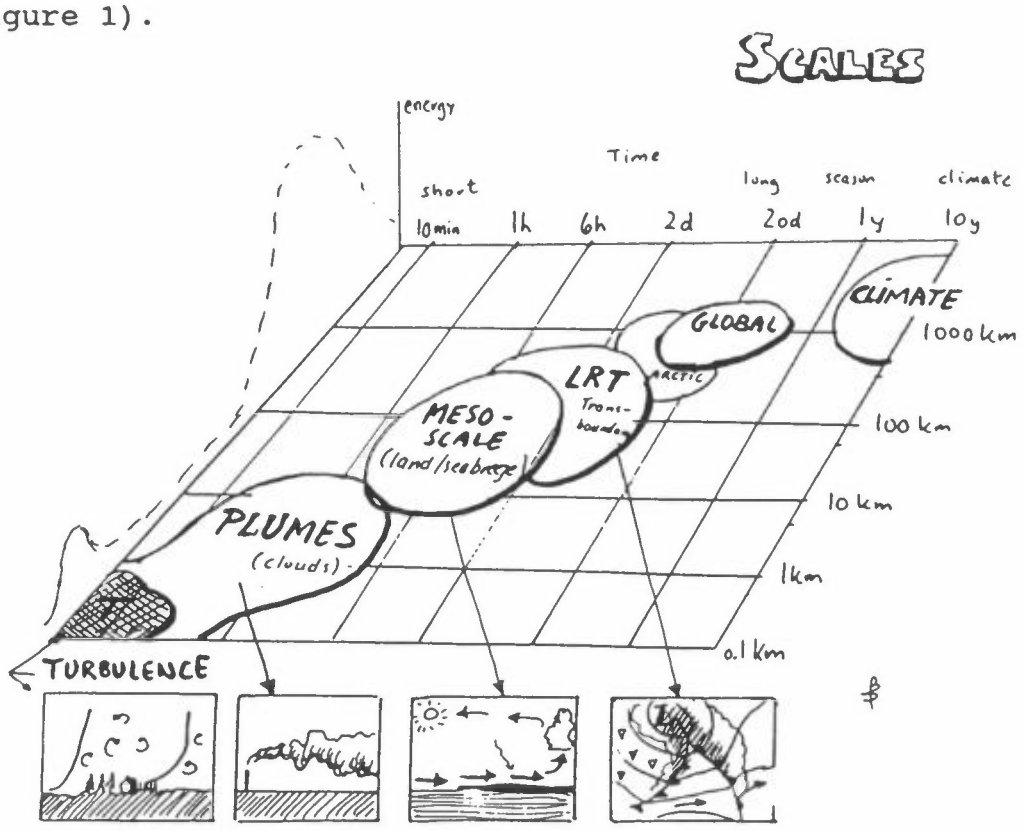


Figure 1: Meteorological scales in space and time.

The variation of air motions (wind) on all scales is the most important factor deciding the air pollution concentrations at a certain receptor. The wind observed at a certain point is the sum of several effects:

- large scale wind (geostropic)
- roughness change
- thermally driven local winds
- radiation balance
- topographical features (deformation, channeling ...)

2 LARGE SCALE WIND PATTERNS

We know that air motion requires a force and the wind result of an equilibrium produced by pressure, Coriolis, and friction forces. The pressure forces are caused directly by the existence of high and low pressure regions in the atmosphere, familiar to us from any weather map. In the Northern Hemisphere the air blows counterclockwise around low pressure centers while in the Southern Hemisphere the air blows clockwise. In the middle latitudes the low pressure centers, referred to as cyclones, tend to move northward and eastward.

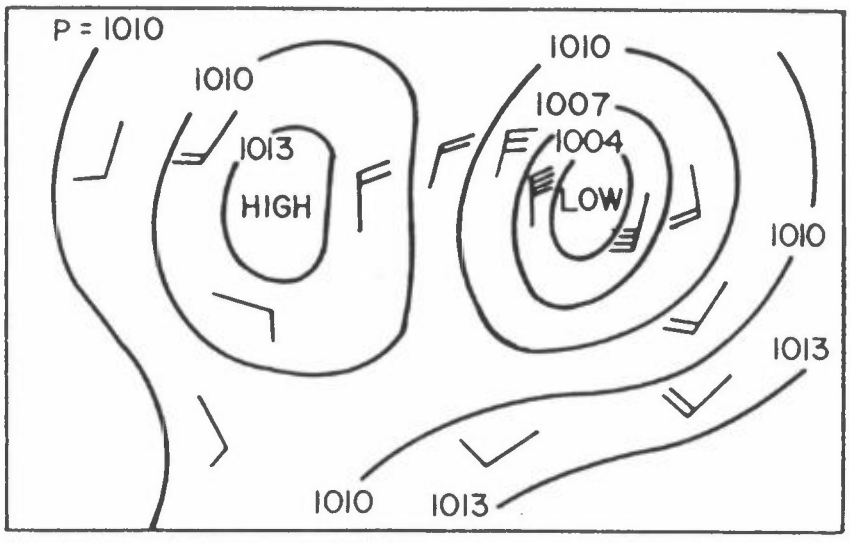


Figure 2: Typical pressure patterns and the associated wind field.

Cyclone here refers to large-scale air masses and not to the violent but small tornados. High-pressure regions are called anticyclones and these are often the source of temperature inversions. An inversion limits the atmosphere available for dilution of pollutant emissions. In anticyclones the air moves clockwise in the Northern Hemisphere. Weather maps show these regions of high and low pressure and also denote wind direction and magnitude by means of vectors with small marks across them. The more marks the higher the wind speed. In the Northern Hemisphere, shown in Figure 2, winds blow so that low pressure areas are to the left-hand side, that is, counterclockwise, and high pressure areas are to the right hand side, that is, clock wise.

The equilibrium between the pressure forces and Coriolis forces (earth rotation) with the wind blowing parallel to the isobars with low pressure on the left is resulting in a balanced wind called the gradient wind. Such winds are found in the upper layers of the atmosphere. Near the surface of the earth, the friction force comes into play. This force causes a change in wind velocity and wind direction

The wind speed must be zero at the earth's surface and then rise to the gradient value at a height which is usually a few hundred meters. The friction force causes the air to be turned slightly towards the low pressure. In general, the air flow at the earth surface is directed to the left of the gradient flow and is about 15° by day over smooth surfaces, changing to as much as 50° by night over rough terrain (Figure 3).

The effect of terrain roughness on the wind speed profile is shown in Figure 4.

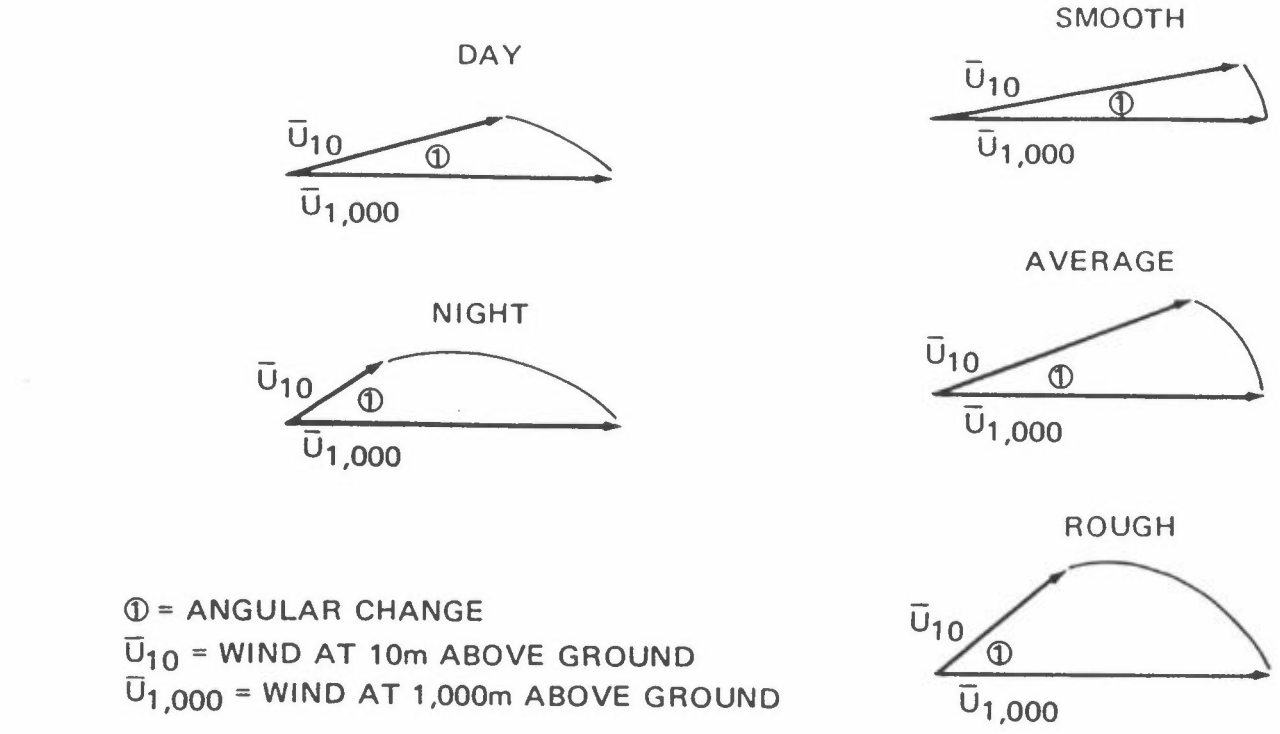


Figure 3: Change of wind direction with height. Not only the wind speed, but the direction changes with height as a result of frictional forces.

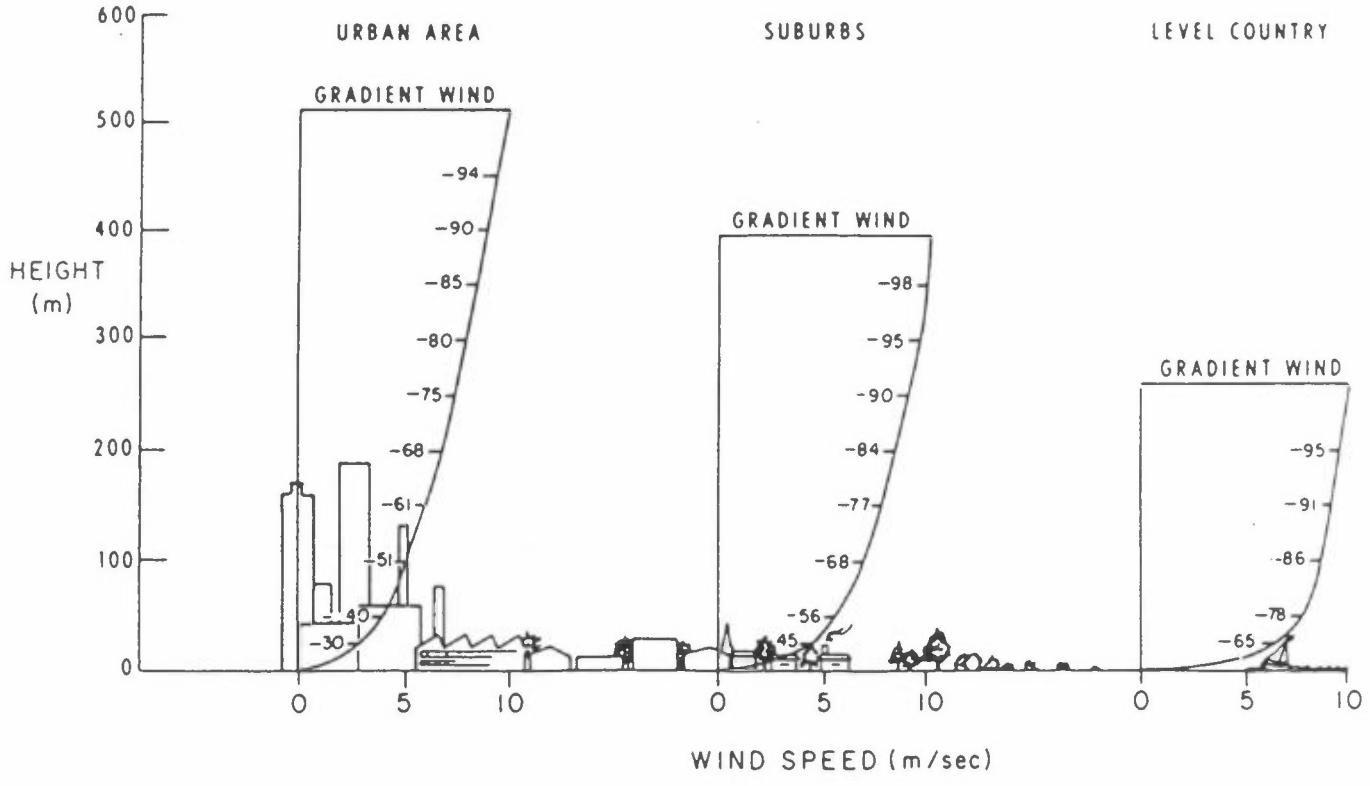


Figure 4: Effect of terrain roughness on the wind speed profile. With decreasing roughness, the depth of the affected layer becomes shallower.

3 LOCAL AIR FLOWS

The local air flow as we observe it from a wind recorder is influenced, in addition to the large scale pressure pattern, earth rotation and surface friction by:

a. Thermally driven wind systems
   - land/sea breeze
   - montain/valley wind
   - upslope/downslope wind

b. Deformation of stream
   - channelling
   - separation

c. Stagnation

3.1 LAND/SEA BREEZE

One such local effect is the sea-land or on-shore, off-shore breeze. In large bodies of water the thermal inertia of the water causes a slower temperature change than on the nearby land. For example, along an ocean coast line and during periods of high solar input, the daytime air temperature over the ocean is lower than over land. The relative warm air over the land rises and is replaced by cooler ocean air. The system is usually limited to altitudes of several hundred meters which, of course, is where pollutants are emitted.

The sea breeze or on-shore breeze develops during the day and is strongest in mid afternoon. At night the opposite may occur, although usually not with such large velocities. At night the ocean is relatively warm and the breeze is from the cooler land to the warmer ocean. The on-shore breeze is most likely in the summer months; the off-shore land breeze may occur in the summer but is more likely in winter months. The action of such a wind-topographic system is shown in Figure 5.

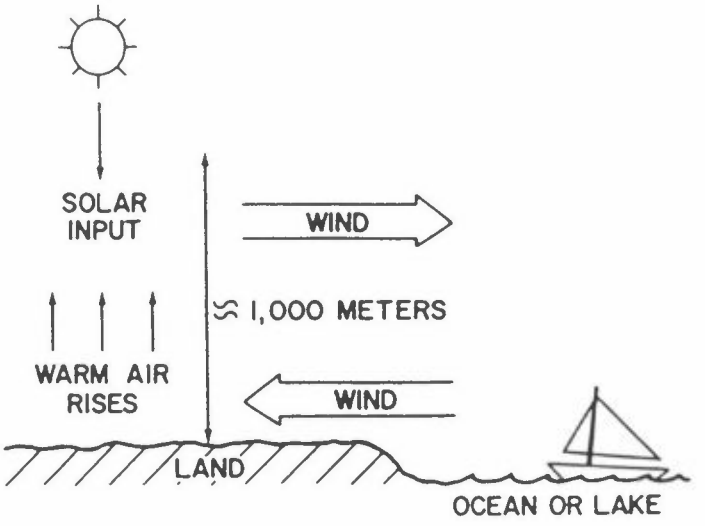


Figure 5: Sea breeze during the day

3.2 TERRAIN INDUCED AIR FLOW

Different terrain-induced airflow phenomena will be discussed in the following:

- mountain and valley thermal wind systems driven by solar heating of the valley slopes during the day and cold air drainage at night. The downslope drainage flow during night time is usually somewhat simpler to treat, and appears more frequently in the literature, than the daytime upslope warm convective local winds. Modelling of these wind systems has mainly been diagnostic rather than predictive.

- deformation of streamlines - channeling through valleys, airflow around and over obstacles have largest implications on the transport, but also on the dispersion through the processes of entrainment and turbulence. In neutral and unstable conditions these wind fields can be simulated through the interaction between the free atmosphere and the surface layer.

- plume impaction on terrain surface may result in high ground level concentrations. This is usually of concern in short time periods only.

- severe atmospheric stagnation may persist for days in lower, sheltered regions of complex terrain under certain large scale meteorological conditions, and can give rise to air pollution episodes. Wind field analysis has to be supplied with data on mixing heights on time and space variation of vertical temperature profiles.

The mountain/valley wind system is driven by differences in the energy (heat) exchange at the surface.

The theory of mountain winds has described a double system of periodic winds; during the day there are upslope and up-valley winds; and at night downslope and down-valley winds. The slope winds are always initiated first, then the valley winds follow. During the course of the day there is a change taking place with a phase difference. The diurnal pattern of these wind systems is sketched in Figure 6.

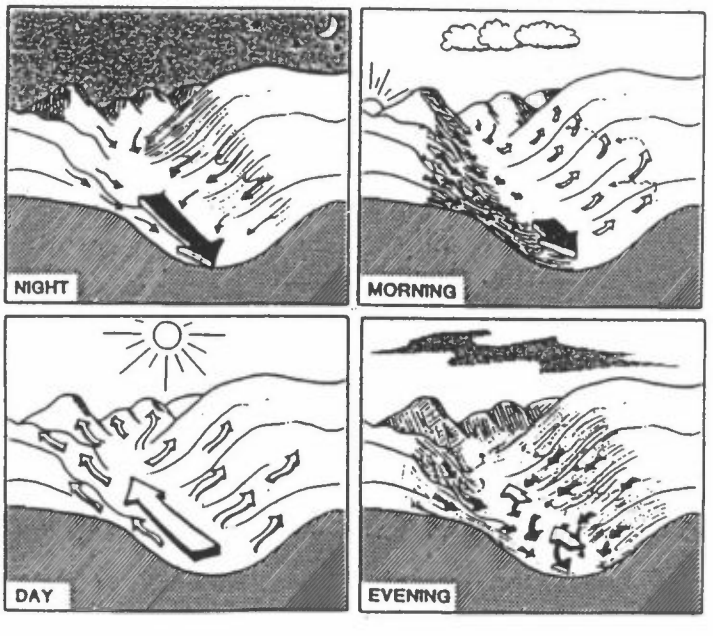


Figure 6: A typical diurnal pattern of the mountain/valley wind system.

Dependent upon the valley axis orientation and the surface, various cross-valley circulation systems might occur during the transitional periods. A valley wind system is decisively influenced by slope exposure to sun heating and direction of the valley. It is, therefore, difficult to design generally applicable, realistic models of valley winds.

A brief outline of the physics behind the driving forces; the upslope and drainage winds will be given before describing some observational facts about the mountain/valley wind system.

3.2.1 Upslope winds

In the morning hours on clear days the absorption of radiation on the sunny slopes leads to warming of the air near the surface. The "free atmosphere" air at the same height above sea level thus will be colder, and a circulation of air developes with a current up the slope. An example of the morning hour heated upslope current is shown in Figure 7.

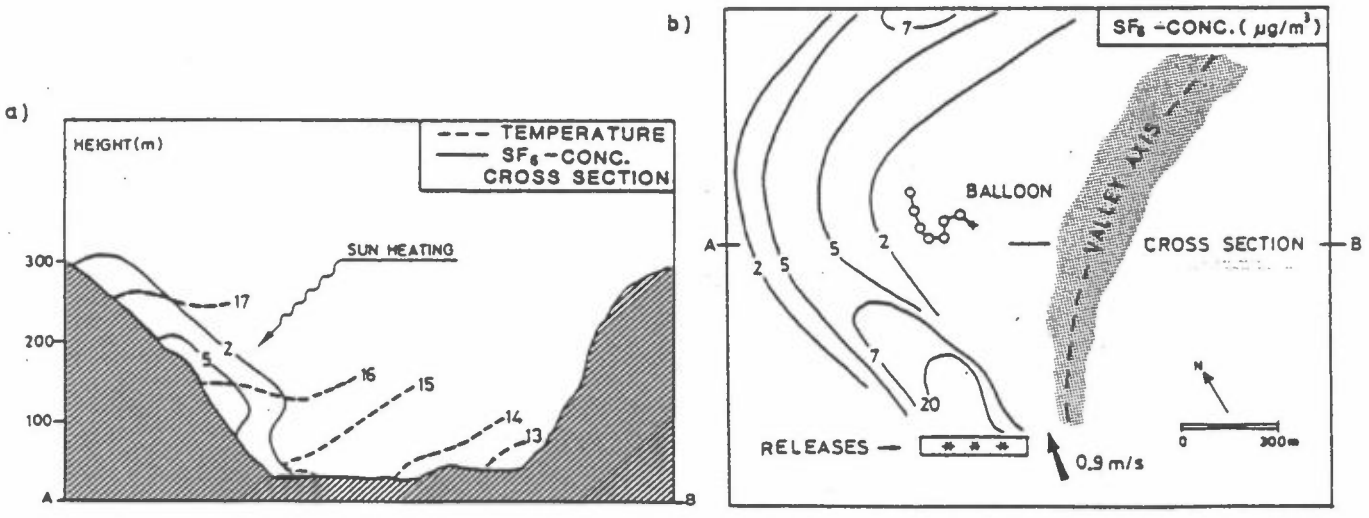


Figure 7: Morning hours upslope wind, on 14 June 1978, Høyanger valley.
a) Valley cross sections of temperature (°C) and SF6 concentrations ($\mu g/m^3$).
b) Ground level concentrations of SF_6 ($\mu g/m^3$)

SF_6 tracer was released at the valley bottom, and was brought by the upslope flow of the heated (left) side of the valley up to a level of about 300 m above the valley floor, and then brought into the valley with a weak up-valley air current.

The observation of slope winds within valleys has usually been a secondary aim when investigating the total mountain/valley wind circulation. Therefore, very few good observations exist especially of upslope winds.

3.2.2 Downslope drainage winds

It is somewhat simpler to treat nighttime downslope winds than the daytime convective upslope winds. Well-developed dpwnslope winds have been found despite of a gradient wind speed of up to 10 m s^{-1}.

A simple quantitative analysis of air drainage, starting with the equation of motion, can be expressed by:

$$\frac{du}{dt} + F_x = \frac{1}{\rho}\frac{\delta p}{\delta x} \qquad (1)$$

where u is the horizontal velocity in the x-direction downslope, F_x is the frictional force, ρ is the density and $\delta p/\delta x$ the pressure gradient approximated by:

$$-\frac{1}{\rho}\frac{\Delta p}{\Delta x} = -g\left(\frac{T_1 - T_2}{T}\right) \operatorname{tg}(\pi-\theta)$$

For explanation, see Figure 8.

Introducing a non-adibatic temperature change, given by an equation for radiative cooling, and assuming that the frictional force is proportional to the velocity, Fleagle found that the mean downslope velocity could be expressed by:

$$u = -\frac{c_p C}{ghtan\theta}\left\{1 - \frac{(k_f{}^2+4\omega^2)^{1/2}}{2\omega}\exp(-k_f t/2)\cdot\cos(\omega t - B)\right\} \qquad (2)$$

where $C = \sigma(1-r)(T_s^4 - 0.65T_2^4)/(\rho\ c_p)$,

$\omega = (-k_f^2/4 + g^2 \tan^2\theta / c_p T)^{1/2}$

and k_f a constant expressing the frictional force.

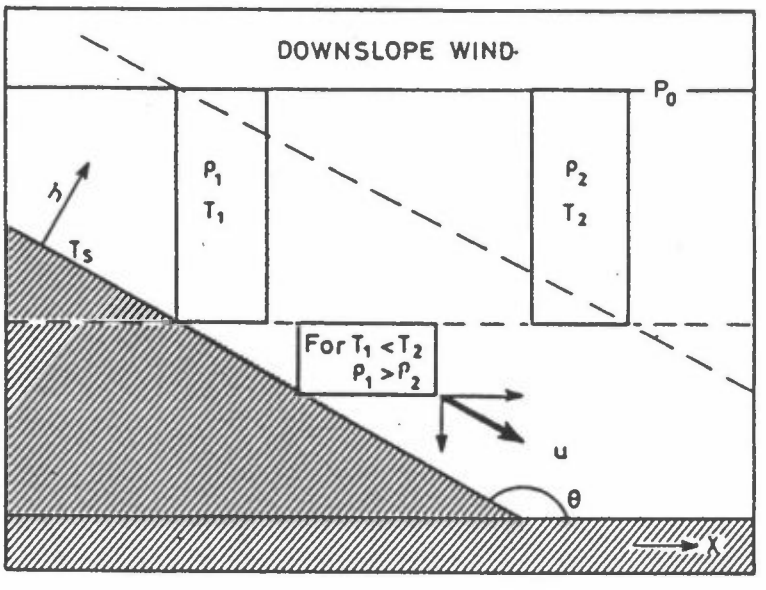


Figure 8: Downslope drainage winds

The mean wind velocity in a cooled layer of air near and along a slope is thus proportional to the net outgoing radiation, and inversely proportional to the thickness of the cooled layer. It begins varying periodically, but becomes gradually constant and inversely proportional to the slope of the surface.

The magnitude and location of the maximum wind velocity (low-level drainage jet) vary as a function of the deviation of the surface temperature from the undisturbed reference state. The development of a drainage flow can thus be predicted, if the surface temperature or heat flux variation, among other parameters, is determined from field experiments. These models, however, can only predict the gross charcteristics of undisturbed drainage flows.

Model predictions of realistic drainage winds can serve only for clarification and demonstration purposes, and have to be adjusted to observations. Field observations are usually not made on anything resembling simple slopes.

Some of these difficulties are revealed in Figure 9 from measurements at night-time in a Norwegian valley.

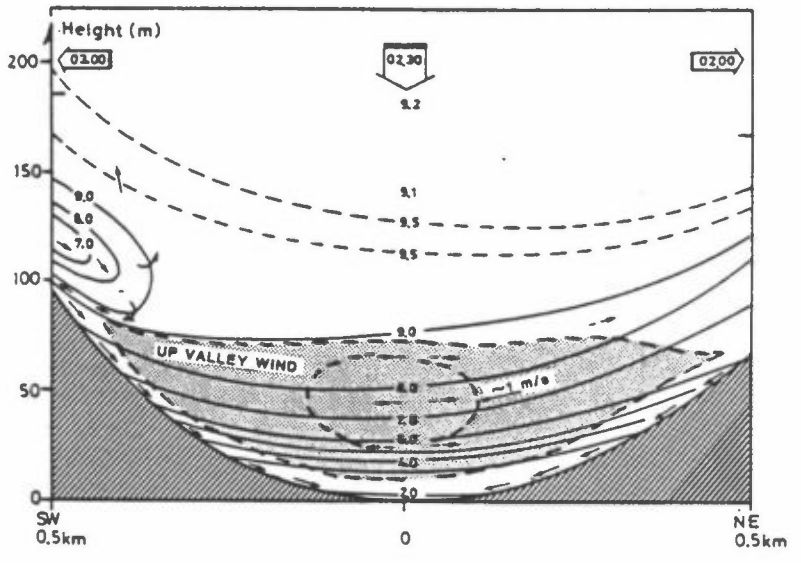


Figure 9: Cross-valley isotherms at 0230 hrs. Arrows indicate observed and assumed cross-valley winds; shaded area indicates observed up-valley airflow.

The strongest cross-valley drainage flow was observed along the slope, where the air was cooled by radiative heat loss at the surface and tubulent heat exchange. A cold air pocket was moving downwards along the SW slope at a height of about 25 m above the surface. The observations indicate a tendency of the cold air to move along isentropic surfaces (approximately along the isotherms). The apparent drainage along the total length of the slope might thus be caused by cold air released at alternating intervals at the valley sides.

3.2.3 Along-valley winds

The combined effect of the slope wind systems is the total mountain/valley wind system, as illustrated in Figure 6. This wind system is most important for air pollution transport and diffusion in valleys, as most of the low level sources (traffic, heating, etc.) often are located along the valley bottom.

Surprisingly few observations exist of the vertical structure of the valley wind. In most of the cases reported, three "layers" seem to exist: the near surface up- or down-valley flow, which varies in thickness from day to night, the "anti wind" and the gradient wind above. From observations, however, there is no general structure.

An example of a time cross section of the up/down valley component of the wind, measured in the middle of a U-shaped valley, is shown in Figure 10.

The observed temperature profiles in Figure 10 indicate unstable convective conditions in the valley during daytime, and stable conditions at night with a temperature inversion extending to about 100-200 m above the valley floor. These down-valley stable cold air currents at night might be critical for the impact of air contaminants from low level sources near the valley bottom.

Along a sloping valley floor the detailed flow pattern of the down-valley wind might look rather complicated. As the surface cools, there will be a downward flux of cold air. This cold air might be dammed up by minor roughness elements, valley narrows or forest canopies. As earlier noted, the flow has a tendency to follow the isentropic surfaces, causing relatively warmer air in the down-valley current to overflow the cool air near the surface. This is also illustrated in Figure 11 from observations in a Norwegian valley.

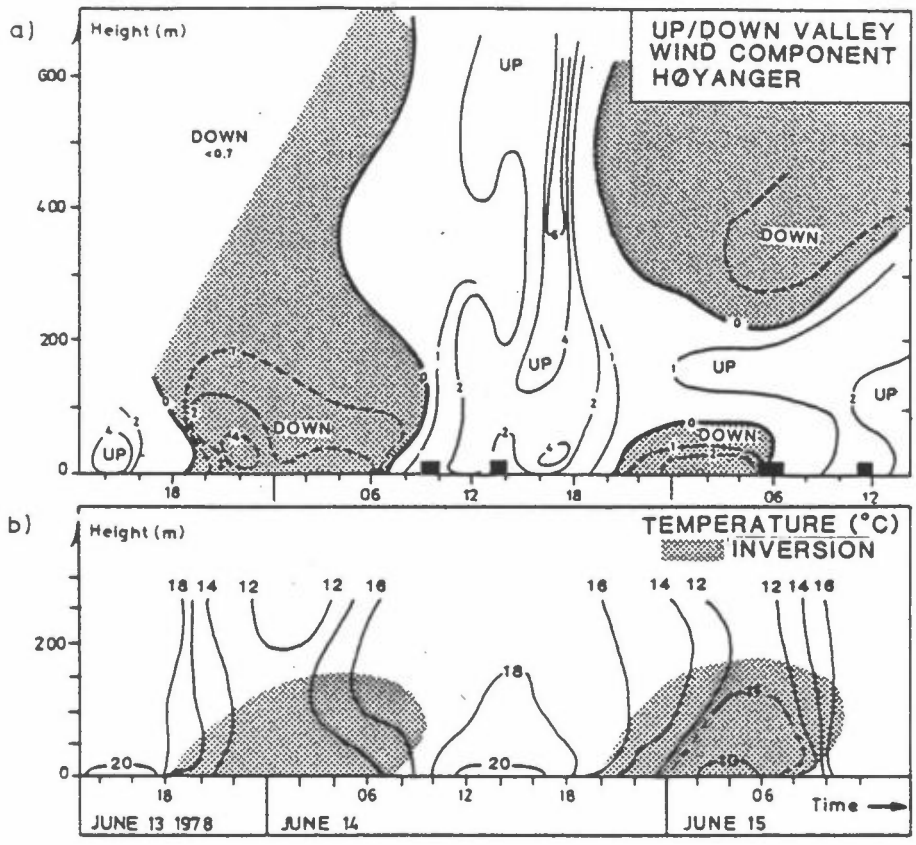


Figure 10: Wind and temperature time cross-sections measured in the middle of a U-shaped valley in June 1978.
a) Up/down valley component of wind (numbers indicate wind velocity m/s).
b) Temperature profiles (inversion layers are shaded).

Wind data from different valleys indiactes that the kinetic energy of the mean and turbulent motions in the valley is inhomogeneous and non-stationary. An example of daytime up-valley and nighttime down-valley flows is shown in Figure 12. The down valley mountain winds generally associate with horizontally convergen flow, whereas the up-valley associate with a horizontally divergent flow. This is seen at the midvalley stations A, B and C in Figure 12. This daytime divergence and nighttime convergence influence the dispersion in the valley, resulting in a generally greater mean spread in the afternoon than in the morning hours.

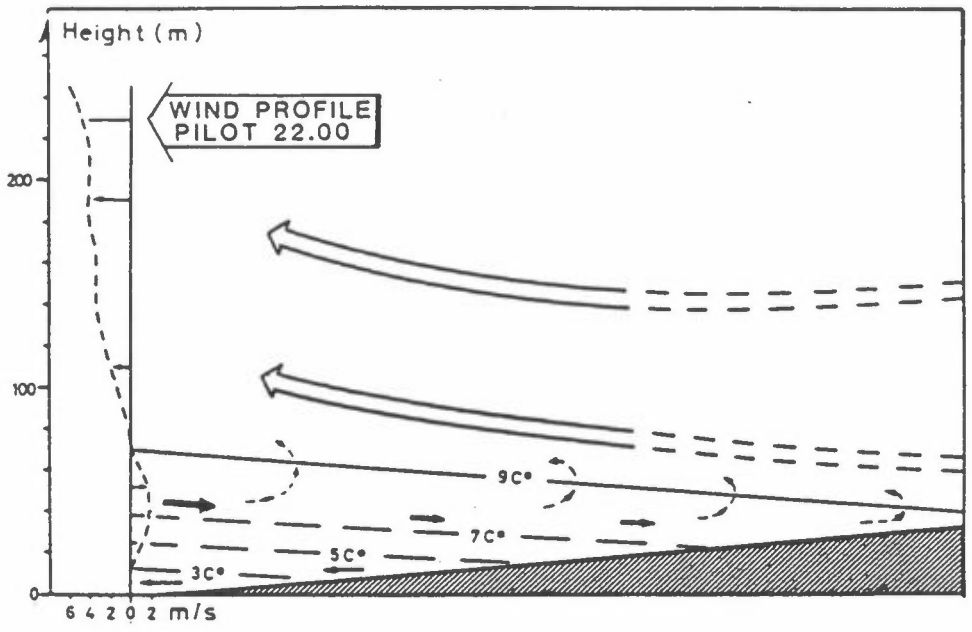


Figure 11: Along-valley cross section of air flow and temperature at night.

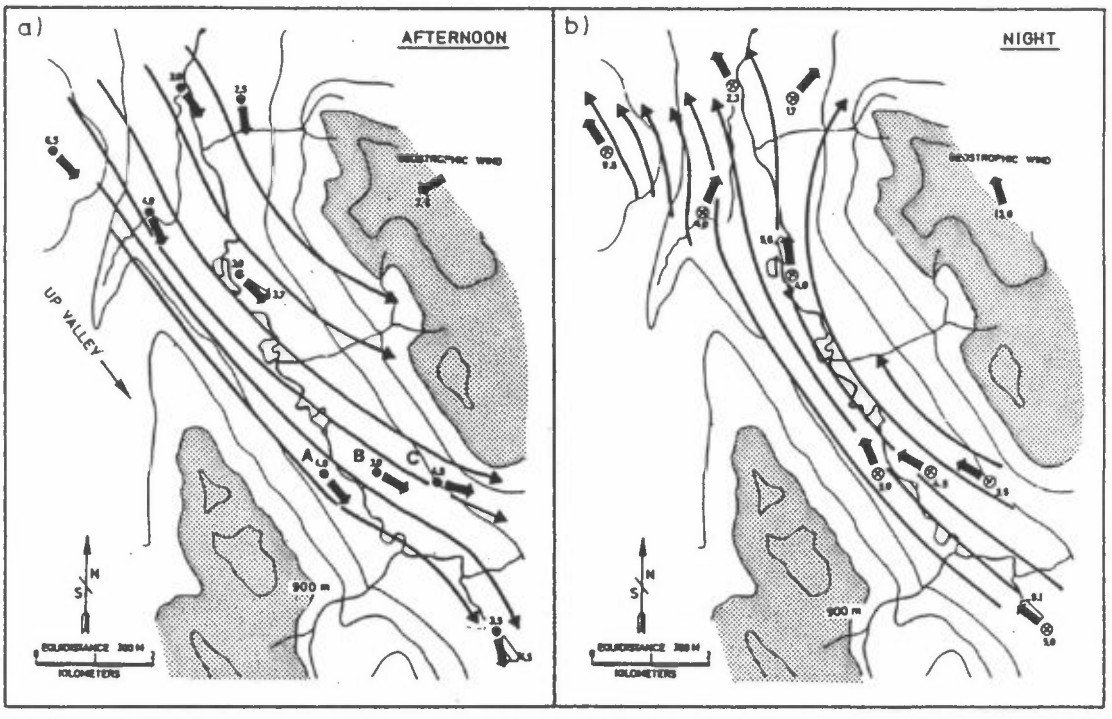


Figure 12: Air flow at the 10 m level in a narrow U-shaped valley.
a) Late afternoon
b) After midnight

3.2.4 Deformation of stream lines

Most air flows pass over underlying surfaces of changing roughness, elevation (topography), and varying heat balance. This section will deal with flow phenomena resulting from changes in the surface structure, disregarding any effects of differential heating. When referring to observations, however, one has to realize that all these processes may be present. The main types of deformation are illustrated in Figure 13.

The topographical inhomogeneities result in large spatial variations in both wind speed and direction. The wind direction changes are most pronounced in valleys where channelling is effective. The wind speed also changes as flow passes across hills or obstacles. When the streamlines no longer follow the contour of the hill, the primary flow is said to "separate". This separation might cause large turbulent eddies to develop behind the hill. If pollutants are released in the turbulent wake zone, high ground-level concentrations may be found.

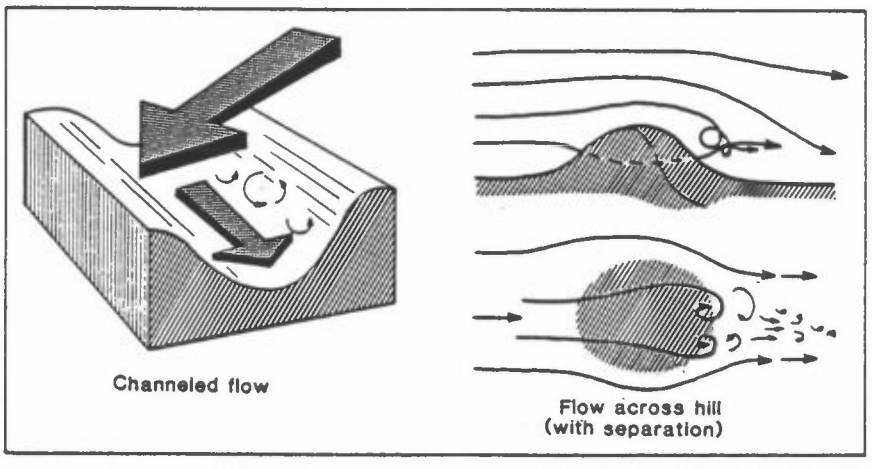


Figure 13: Deformation of flow due to chanelling and airflor around and over hills (or obstacles).

3.2.4.1 Channelling

When examining Figure 12, the channelling of the wind along the
valley is obvious even when the geostropic (large scale) wind is blowing perpendicular to the valey. The effect of channelling is also evident when analyzing climatological data from valleys, as illustrated in Figure 14.

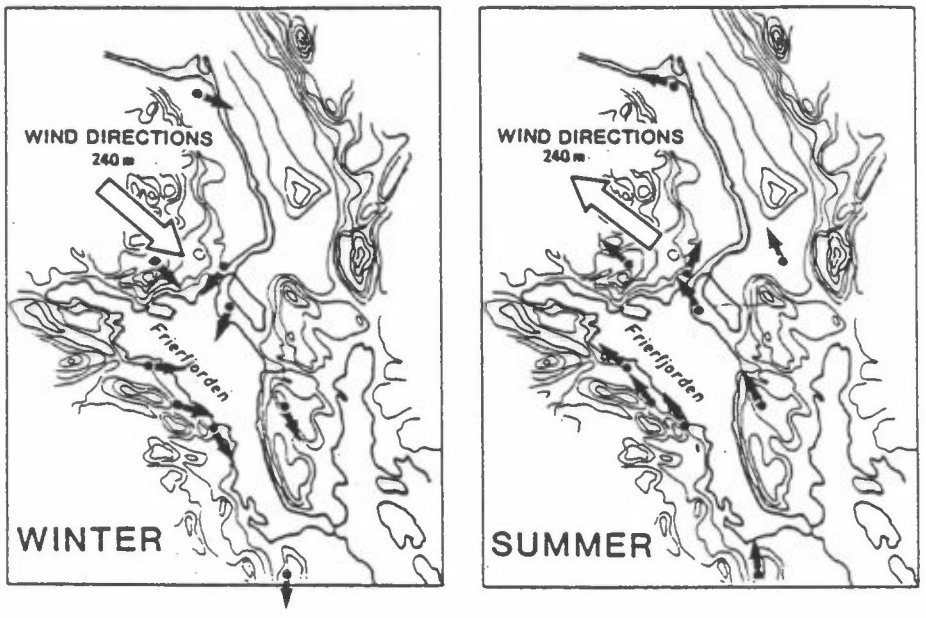


Figure 14: The predominant wind directions in Telemark, Norway during winter and summer, measured 10 m above the surface. The white arrows show the prevailing wind direction in the larger scale valley system, as measured at 240 m.a.s.l.

3.2.4.2 Flow separation

When the flow streamlines no longer follow the contour of a hill, the primary flow is said to "separate". Separation occurs when the gradient of velocity at the boundary becomes zero, as illustrated in Figure 15.

Flow separation is commonly observed on the lee side of mountains and is especially pronounced to the lee of sharp crests.

The separated regime is charcterized by high mixing rates, lower velocities, and reversed eddy flow. Figure 16 summarizes some effects of separation of the boundary layer.

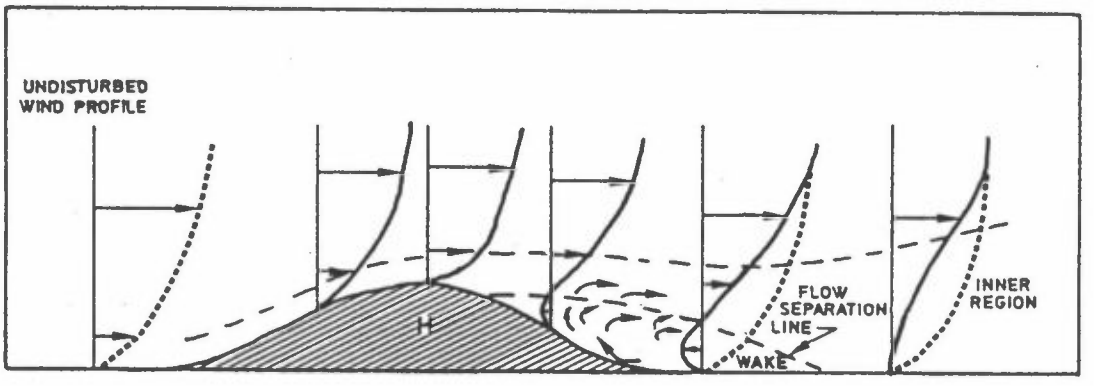


Figure 15: Typical wind profiles in a flow across a hill.

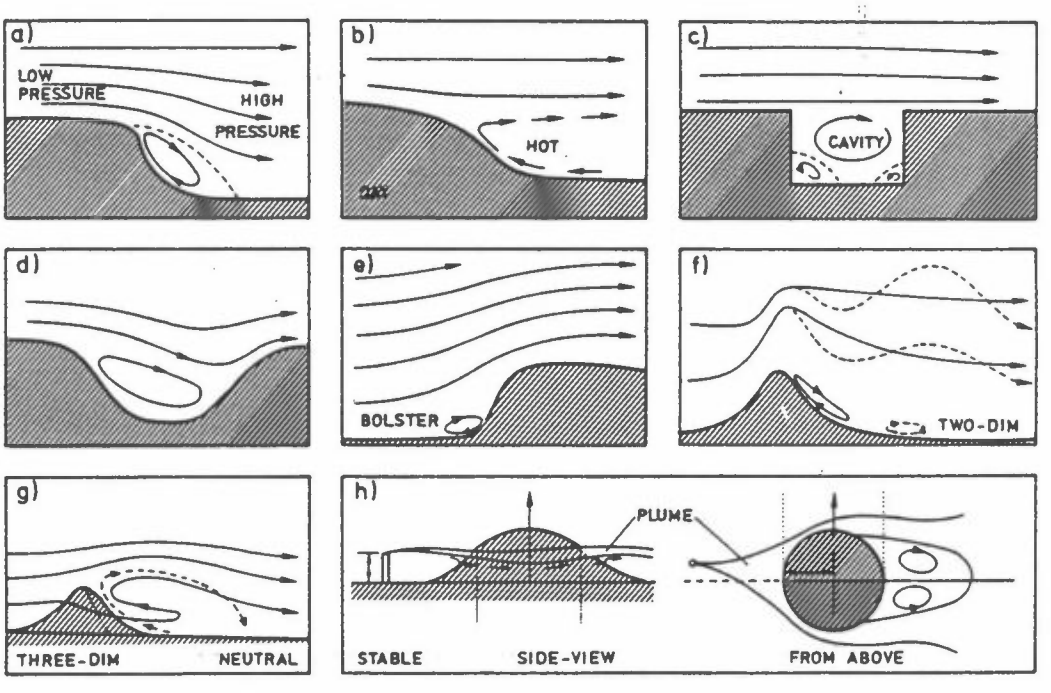


Figure 16: Various aspects of flow separation in complex terrain.

The main aspects shown are that:

a) Separation occurs in regions where the fluid is flowing up the pressure gradient;

b) For flow up a slope, heated by sunshine, separation occurs near the top;

c) In a valley with steep cliffy sides, or in street canyons, cavitation might occur, and the flow becomes very complicated;

d) In an actual valley with cross-valley external wind, the flow may be very unsteady; the eddy may fill the valley at onne moment and then rejoin near the foot of the wind facing slope, gusting from time to time;

e) There might also be eddies at the foot of wind-ward facing slopes, called "bolsters";

f) The wind accelerates over the top of a two-dimensional hill, and lee waves are often observed. This phenomena depends upon the non-dimensional Froude number: $F_r = U/NH$, where U is the free-stream wind speed, H is the hill height and N is the Brunt-Väisälä frequency: $N = [(g/T)(\delta\theta/\delta z)]^{1/2}$. Waves behind mountain ridges usually occurring at $F_r << 1$, are not covered in this presentation.

g) The flow across a three-dimensional hill has been studied in great detail at Cinder Cone Butte, Idaho. In neutral flow for $F_r \geq 1$ the air flows around the hill and up the sides to the top, where it may separate. The neutral flow over three-dimensional hills is similar to that of two-dimensional hills, except for the wake structure.

h) When $F_r << 1$, stratified flow over three-dimensional hills does exhibit unique characteristics, as indicated in h) of Figure 16. Below the top of the hill the flow tends to move in horizontal planes because of the stratification. At each level the air moves around the hill as if it were a vertical cylinder with a cross-section of the hill at that level. This pattern breaks down in two places: over the top of the hill, and on the lee side where the horizontal flow

separates. There is a critical release height, h_c where plumes will travel over, rather than impinge on the hill:

$$h_c > (H - U/N) = H(1-F_r).$$

For air polution evaluations, the most important feature of flow separation is the downwind wake effect behind hills. From observations in the atmosphere and wind tunnel studies the following general features are observed:

- the region of separated or reversed flow may extend up to 10 hill heights downwind (Figure 17);

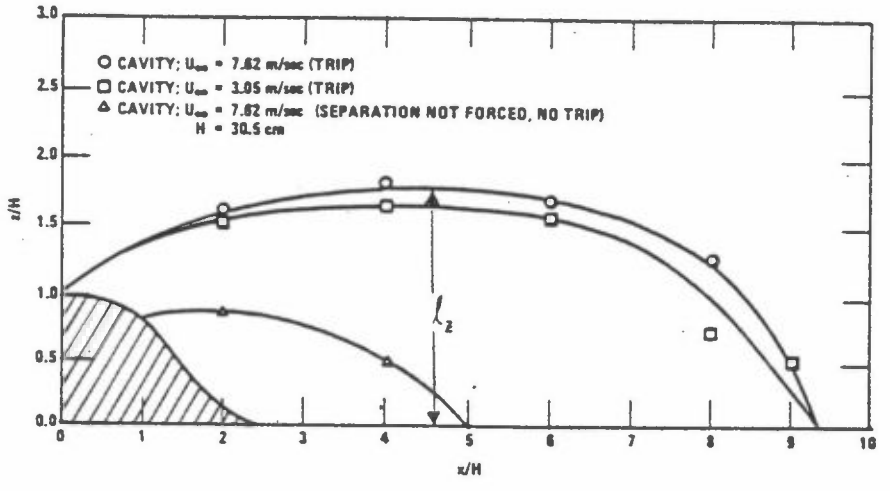


Figure 17: The cavity size in lee of a Gaussian ridge.

- the vertical extent of this region might be from a fraction of the hill height, H, to as much as 2H;

- downwind of the separated flow region the wake region is characterized by a deficit in the mean velocity decreasing

down wind, vigorous turbulence within the wake and an average downwind motion.

A similar separation of flow occurs for flow over a building. Figure 18 shows the flow pattern around a building. The flow separates to form a large "cavity" behind the building. Backflow occurs within the cavity so that downwind sources are carried upwind if emitted in regions of separated flow. Pollution reaching this cavity tends to remain there since very poor mixing between the cavity and the main stream occurs.

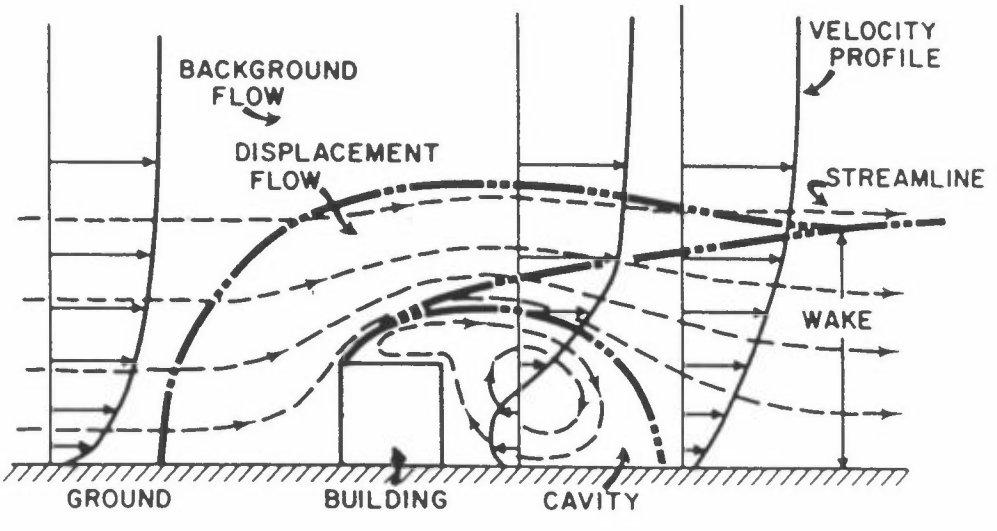


Figure 18: Mean flow around a cubical building. The presence of a bluff structure in otherwise open terrain will produce changes in the wind flow generally similar to those shown.

Figure 19 shows what happends to an upstream source when the separated cavity and wake behind a building interfere with the plume dispersal. Under conditions (a) the stack plume clears the cavity but enters the wake. Downward diffusion is thus increased by mixing occurring in the turbulent wake. In case (b) the plume enters the cavity from the front and high concentrations can then build up along the backside of the building. An industrial plant designer needs to be sure that stack plumes do not interact with the building in this manner. An empirical

rule of thumb for stacks located on or near to a building is that $H_{stack} \geq 2.5\ H_{building}$.

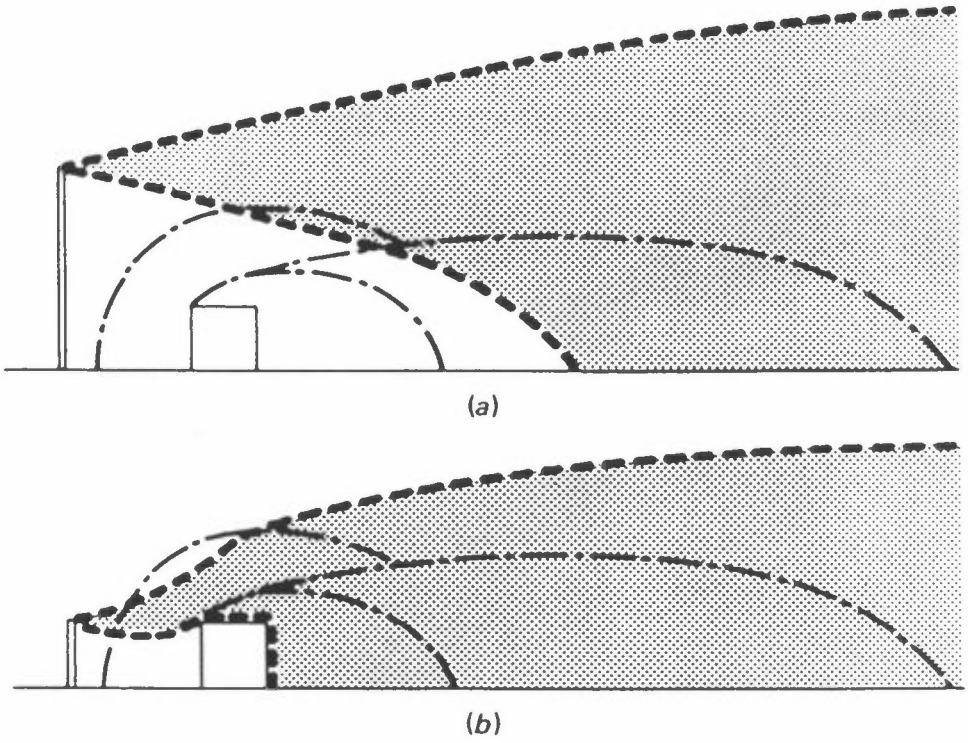


Figure 19: Separation effects on plume dispersion

4 TURBULENCE

In the general wind pattern the smallest scale variations, "in which the instantaneous velocities exhibit irregular and apparent random fluctuations", are usually referred to as turbulence. The turbulent air flow is represented by eddy motions.

An eddy refers to a piece of air which moves randomly in a fluctuating manner just as do the eddies which we picture in turbulent flow in a pipe or over a flat plate. In the atmosphere, however, the eddies can become very large.

During the day solar heating causes thermal turbulence. Turbulent mixing is increased and the wind profile is flatter than

at night. The other type of turbulence, mechanical turbulence, is caused by air motion over the rough surface of the earth, either natural or man made. During high winds we would expect the atmosphere to be well mixed by mechanical turbulence.

The effect of terrain on wind velocity profile was noted in Figure 3. When the surface is smooth the air flow is smooth and the velocity profile becomes very steep near the ground. For rougher surfaces more mechanical turbulence is generated and the velocity profile becomes less steep and reaches deeper into the atmosphere.

The effect of eddy motion is very important in diluting concentrations of pollutants. If a piece of air is displaced from one level to another it can obviously carry momentum and thermal energy with it. It also carries whatever has been placed in it from pollution sources. Thus smoke will be diffused by turbulence in both the vertical and horizontal directions.

The effect of different eddy sizes on a plume is shown in Figure 20.

4.1 MECHANICAL INDUCED TURBULENCE

The mechanical induced turbulence is caused by wind action crossing uneven and rough surfaces. Turbulence is generated by mechanical shear forces at a rate proportional to $(\delta u/\delta z)^2$ (the wind speed profile).

The wind profile gradient is dependent upon the surface roughness and the stability of the atmosphere. Figure 21 shows example of wind speed profiles.

It is possible to use a power law to describe the velocity profile and one such profile is given by

$$\bar{u}_z = \bar{u}_0 \ (z/z_0)^m$$

where m varies from about 0.12 to 0.50 depending on the atmospheric conditions.

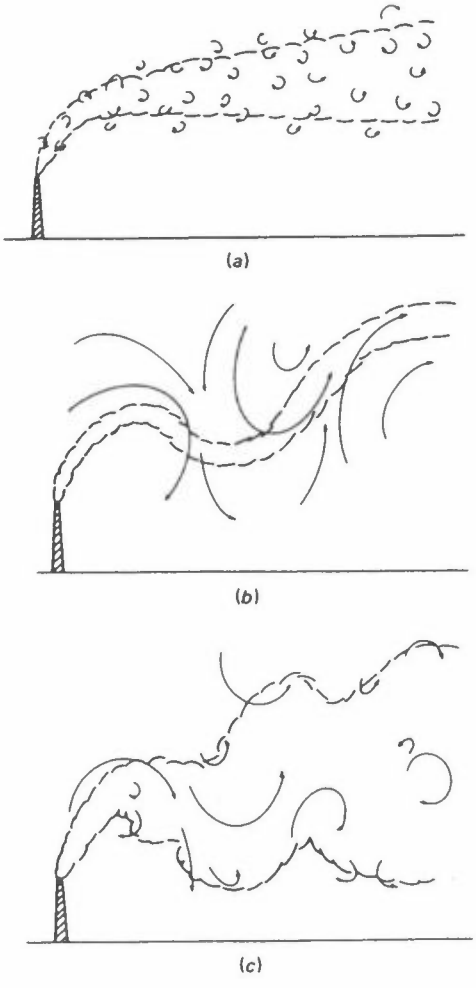


Figure 20: a) Plume dispersing in a field of small eddies. A plume in a hypothetical field of small turbulent motions will move in a relatively straight line, with a gradual increase in its cross section.
b) Plume dispersing in a field of large eddies. If the eddies are all very large compared to the plume dimensions, the plume will grow very little in size, but will meander wildly.
c) Plume dispersing in a field of varied eddies. The typical daytime atmosphere has eddies of an infinite variety of sizes, and a dispersing plume both grows and meanders as it moves downwind.

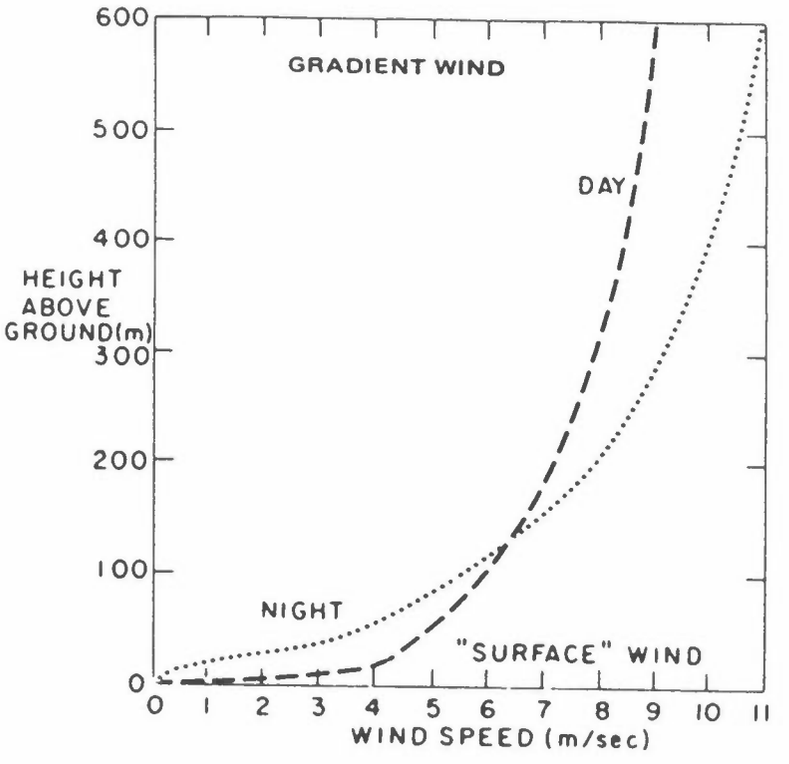


Figure 21: Change of wind speed profile with stability. The frictional drag reduces the wind speed close to the ground below that found at the gradient level.

The turbulent velocity profile for flow over a plate is sometimes taken as following a 1/7 power which would correspond to m=0.14. For a smooth surface with an adiabatic lapse rate in temperature, the 1/7 profile is a good approximation.

4.2 THERMALLY INDUCED TURBULENCE

Change of temperature with altitude has a great influence on the generation of turbulence, and thus on the vertical motions and vertical dispersion of air pollutants.

Meteorologists distinguish three states of the atmospheric surface layer; unstable, neutral and stable conditions. In the neutral atmosphere the temperature decreases linearly with height. Assuming that the surface pressure P= 1000 mb and the

corresponding temperature is θ the temperature can be expressed by:

$$T = \theta \ (p/1000)^{\kappa}$$

The temperature θ is called potential temperature. The potential temperature is that temperature a parcel of air/gas would have if it were compressed (expanded) adiabatically (with no heat added) from a given state p,T to a pressure of 1000 mb. For dry air $\kappa \simeq 0.286$. The temperature gradient for the dry near neutral atmosphere is: $\delta T/\delta z = -0.98$ deg/100 m.

Figure 22 shows the environmental lapse rates that illustrate the three stability conditions.

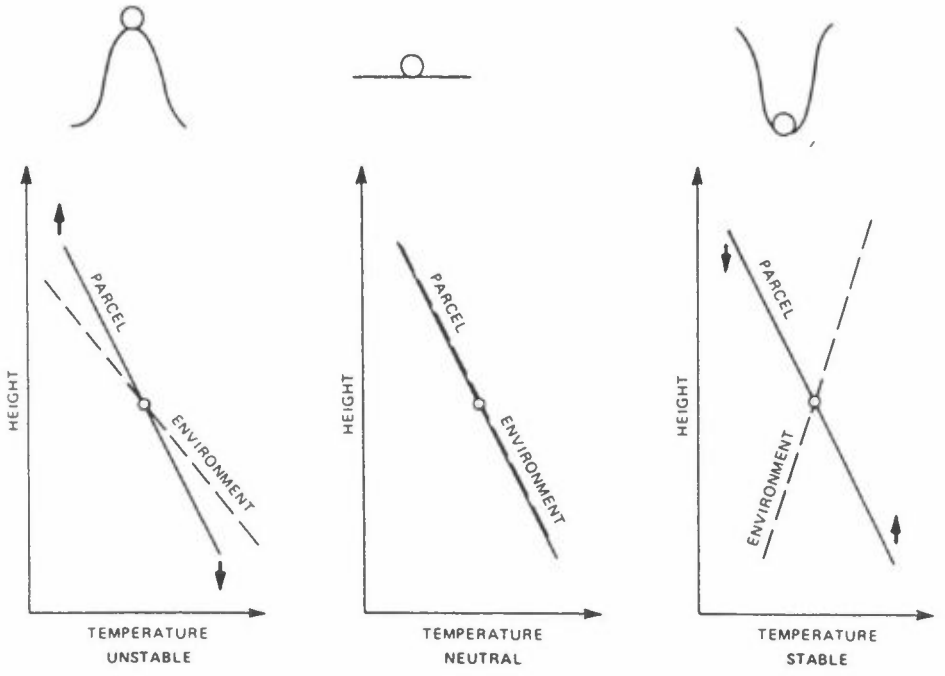


Figure 22: Illustration of unstable, neutral and stable environmental temperature profiles (- - -). An air parcel moved adiabatically, cools as it rises vertically (———).

In each example the parcel originates at the height indicated by the circle in the figure; at this height the temperature of

the parcel is the same as that of its environment. If the density of the parcel is less than that of its environment ($\rho_p < \rho_e$ or $T_p > T_e$), then the parcel is accelerated upwards. If the density of the parcel is more than that of its environment ($\rho_p < T_e$), then the parcel is accelerated downwards. If the density of the parcel is the same as that of its environment ($T_p = T_e$), then the parcel continues at its original speed. For the example of the unstable layer, the parcel is continually accelerated away from its origin. The example of the neutral layer shows that the temperature of the parcel is always the same as that of its environment, and there is no force on it.

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 actual distribution of temperature in the vertical is known as the "environmental lapse rate". This seldom approximates the adiabatic lapse rate in the lowest 100 m over any extended time period. Examples of typical environmental lapse rates are shown in Figure 23. The different atmospheric conditions (temperature profiles) also act different on vertical plume dispersion.

On days when strong solar heating is occurring or when cold air is being transported over a much warmer surface, the rate of decrease of temperature with height usually exceeds -1 °C/100 m, implying that any small volume displaced upwards would become less dense than its surroundings and tend to continue its upward motion. A superadiabatic condition favours strong convection, instability, and turbulence. Superadiabatic conditions are usually confined to the lowest 200 m of the atmosphere.

A neutral condition in which the lapse rate in the atosphere is nearly identical to the dry adiabatic lapse rate, implies no

tendency for a displaced parcel to gain or loose buoyancy. neutral conditions are associated with overcast skies and moderate to strong wind speeds.

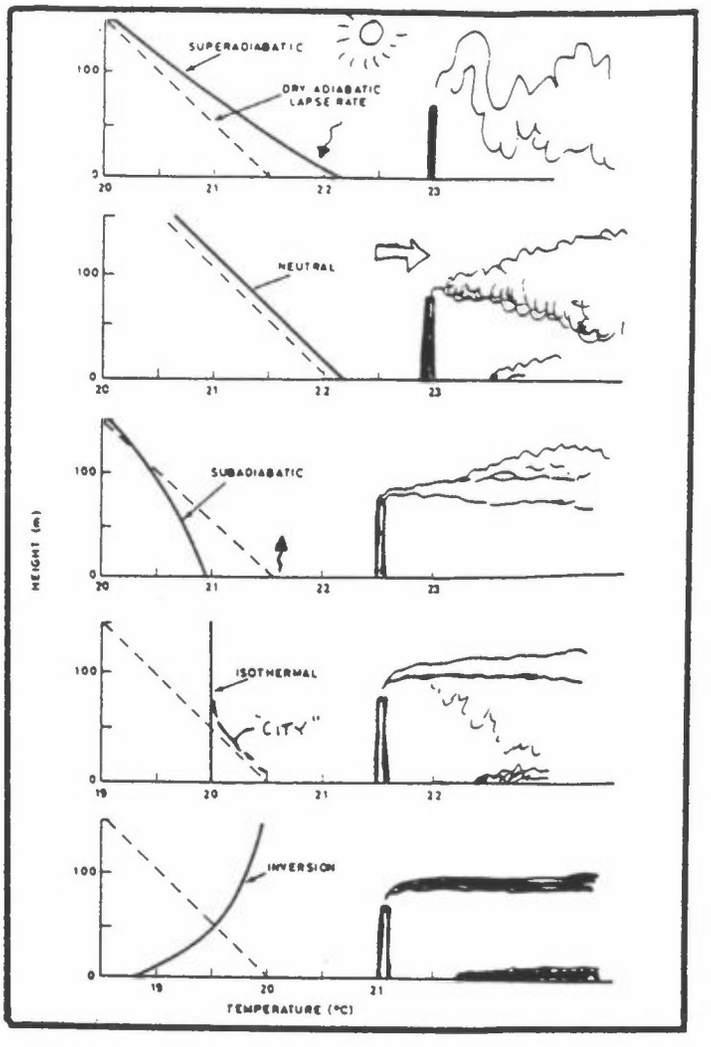


Figure 23: Typical environmental lapse rates and corresponding plumes.

An atmosphere in which the temperature decreases more gradually than -1 °C/100 m is actually slightly stable, since a small parcel displaced upwards will become more dense than its surroundings and tend to descend to its original position, whereas a parcel displaced downwards will become warmer and rise to the original level.

When the ambient temperature is constant with height, the layer is termed isothermal, and as in the subadiabatic case case

there is a slight tendency for a parcel to resist vertical motion.

A stable atmospheric layer in which temperature increases with height strongly resists vertical motion and tends to suppress turbulence. It is therefore of particular interest in air pollution, since it allows very limited dispersion. There has also been much confusion over different types of temperature inversions, and clarification is therefore particularly in order (Figure 24).

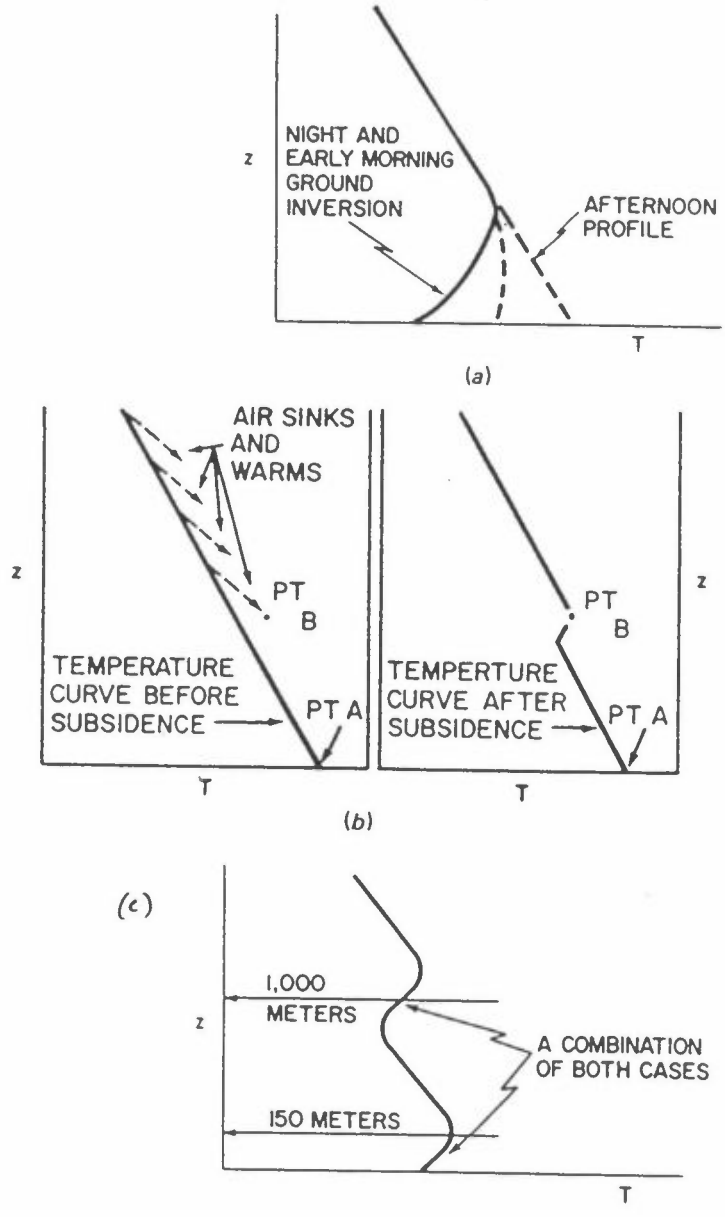


Figure 24: Temperature inversions. (a) During the day. (b) The sinking of air leads to warming aloft the formation of inversions. (c) A combination of cases.

5 MEASUREMENT OF METEOROLOGY

Meteorological measurement data represent vital input to air pollution models. Meteorological data are collected for different purposes:

- local meteorology (dispersion characteristics),
- climatic data (trend analyses, respresentativity)
- synoptic scale (large scale weather)
- upper air (profiles of wind and temperatures, mixing height, upper air wind).

The following data should be collected:

- wind speed,
- wind direction
- temperature
- temperature gradients
- turbulence
- mixing heights
- radiation
- humidity
- precipitation

Automatic weather stations with sensors mounted along a mast should be a minimum requirement for obtaining relevant meteorological data. The upper level should be no less than 10 m.

Table 1 indicate a minimum measurement programme.

Table 1: Recommended minimum measurement programme. The typical sampling duration should be 10 minutes.

Parameter	Sampling rate (sec.)	Measuring height	Instrument example **)
Wind speed	1 to 5	Upper level	Cup anemometer
Wind direction	1 to 5	Upper level	Wind vane
Longitudinal turbulence	*)	Upper level	Cup anemometer
Wind direction fluctuation	*)	Upper level	Wind vane
Temperature	10	Upper level	Resistance
Temperature difference	10	Upper level to lower level	Fast Thermocouples

*) Estiated from wind speed and direction measurements.
**) Instruments should be well designed for the purpose.

5.1 WIND DIRECTION FREQUENCIES (WIND ROSES)

Annual or seasonal average frequency of wind directions and velocities for a site should be obtained for the nearest representative meteorological station. The standard height of instruments is usually 10 m. On site measurements of wind should be presented as wind frequency distributions. A wind rose is usual a pictorial presentation of how often the wind blows from different directions (Figure 25).

Meteorologists define wind direction as degrees from north in which the wind is blowing from. (90 = wind from east, 180 = wind from south, etc.)

Annual and diurnal variations of the wind have to be taken into account in evaluation of an industrial site. These variations occurs on all scales, and are usually due to differential heating of the different surfaces.

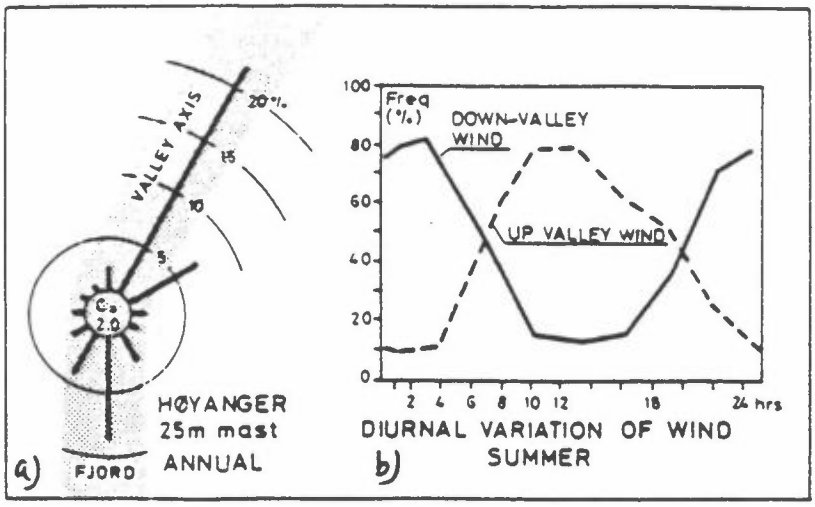


Figure 25: Wind frequency distributions.
a) wind rose for a valley site, representative for an annual average. The bars indicate the frequency in % of wind from each of twelve 30° sectors.
b) Diurnal variation of downvalley and upvalley winds.

5.2 STABILITY

Two parameters for describing the stability conditions or turbulence in the atmosphere have been evaluated by NILU; the vertical temperature difference ($\delta T/\delta z$) and the Bulk Richardson number (Ri_B).

Temperatures measured at different heights above the surface and at different altitudes above the sea level have been used to evaluate the vertical spread of air pollution.

The Bulk Richardson number (Ri_B) includes both thermal induced turbulence (temperature stratification) and mechanical induced

turbulence (wind profile) to describe the dispersion condition in the area.

$$Ri_B = g(\Delta\theta/\Delta z)z^2/(Tu^2)$$

where $\Delta\theta$ is the potential temperature difference measured between the height difference Δz. z is the height above the surface of the measured wind speed (u) and g/T is the buoyancy parameter. The criteria for the four classes of turbulence were:

I	: Unstable	$Ri_B < -0.003$
II	: Neutral	$-0.003 < Ri_B < 0.0075$
III	: Light stable	$0.0075 < Ri_B < 0.05$
IV	: Stable	$< Ri_B$

Typical seasonal and diurnal variations of stability are shown in Figure 26.

Unstable conditions and well developed vertical dispersion of air pollutants most often occurred in the early afternoon in the spring and summer seasons. The Bulk Richardson parameter resulted in a higher frequency of near neutral conditions at daytime, especially in the early afternoon. This was caused by the relatively high wind speeds occurring in the sea breeze at these hours.

At night time hours, stable conditions occurred during all seasons. In the winter season light stable and stable conditions occurred both night and day.

5.3 JOINT FREQUENCY DISTRIBUTION, WIND/STABILITY

When combining the observed data for wind speed, wind direction and stability it is possible to produce a joint frequency distribution, which represents the direct input to the Climatological Dispersion Models (CDM) for estimates of long term average concentration distributions.

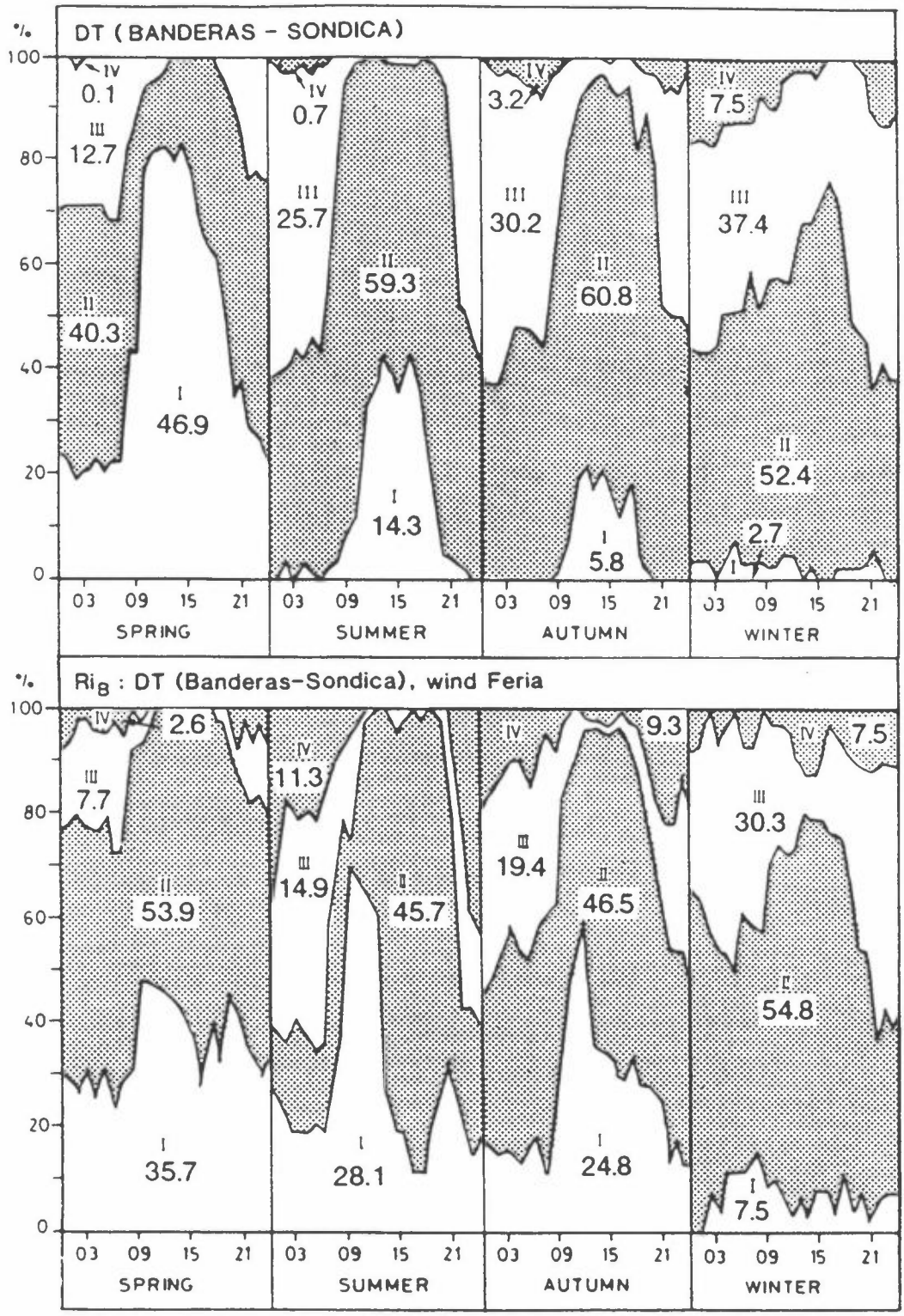


Figure 26: Seasonal and diurnal variation of four classes of stability based upon temperature difference and the Bulk Richardson number.

The meteorological data have been distributed into:

4 classes of stability (STAB)
4 classes of wind speeds (FF)
12 wind directions (DD)

Table 2: Frequency distribution of wind and stability (%)

FF / DD ↓ / STAB→	0-2.0 m/s				2.0-4.0 m/s				4.0-6.0 m/s				>8.0 m/s				Rose
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	
30	0.3	1.1	1.2	0.3	0.6	3.7	4.1	1.2	0.5	1.6	1.6	0.2	0.2	0.4	0.2	0.0	17.6
60	0.2	0.8	0.6	0.2	0.5	1.3	1.3	0.3	0.3	0.4	0.3	0.0	0.1	0.1	0.0	0.0	6.3
Ø 90	0.1	0.5	0.5	0.1	0.3	0.9	0.8	0.1	0.1	0.3	0.3	0.0	0.0	0.1	0.0	0.0	4.3
120	0.1	0.5	0.6	0.1	0.3	1.4	0.9	0.1	0.1	0.4	0.2	0.0	0.0	0.1	0.0	0.0	4.6
150	0.1	0.6	0.6	0.1	0.3	1.7	1.6	0.2	0.2	0.6	0.6	0.0	0.0	0.2	0.1	0.0	7.1
S 180	0.1	0.7	0.7	0.2	0.9	2.7	1.9	0.5	1.3	2.7	1.5	0.1	0.6	2.2	0.9	0.0	17.0
210	0.2	0.7	0.6	0.2	1.7	2.0	1.3	0.3	1.9	2.3	1.3	0.1	0.4	1.6	0.5	0.0	15.0
240	0.3	0.5	0.4	0.1	1.1	0.5	0.4	0.1	0.4	0.4	0.1	0.0	0.1	0.4	0.1	0.0	4.7
V 300	0.2	0.2	0.1	0.1	0.4	0.2	0.2	0.0	0.1	0.2	0.1	0.0	0.1	0.3	0.1	0.0	2.4
330	0.2	0.4	0.3	0.1	0.8	0.8	0.4	0.1	0.5	0.6	0.3	0.0	0.1	0.4	0.1	0.0	5.0
N 360	0.1	0.6	0.8	0.3	0.8	2.8	2.1	0.4	0.5	2.1	1.8	0.2	0.2	0.5	0.4	0.0	13.7
Total	2.3	6.9	7.0	1.8	7.9	18.2	15.2	3.2	5.8	11.8	8.4	0.8	1.8	6.4	2.5	0.1	

1: Unstable 2: Neutral 3: Light stable 4: Stable

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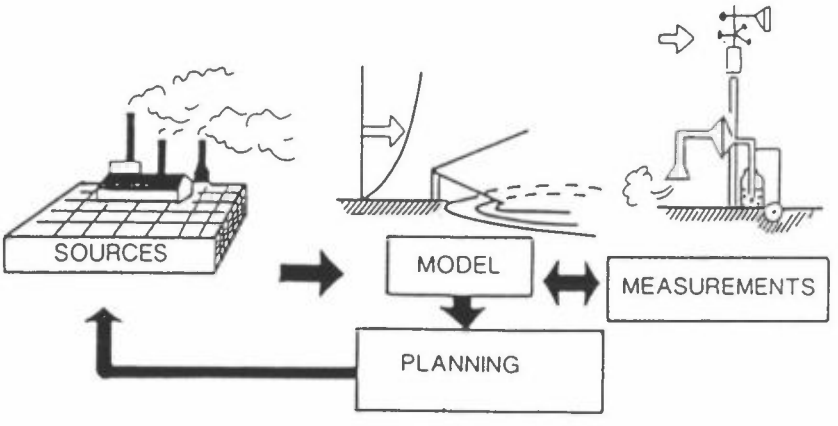
NILU F : 12/92
REFERENCE : O-92014
DATE : MAY 1992

Air Quality Sampling and Analysis

Bjarne Sivertsen



NILU

NORSK INSTITUTT FOR LUFTFORSKNING
Norwegian Institute for Air Research
POSTBOKS 64 — N-2001 LILLESTRØM — NORWAY

AIR QUALITY SAMPLING AND ANALYSIS

1 INTRODUCTION

Air quality studies have been performed by NILU on all scales and for various purposes. We will in this presentation limit ourselves to discuss local air pollution problem.

As in other contexts NILU see the measurement programme as a part of a systematic collection of data for explaining the relationship between emissions and environmental impact.

Only when this relationship is established between sources (emissions) and air quality, we are able to use this information as a planning tool for better air quality (see Figure 1).

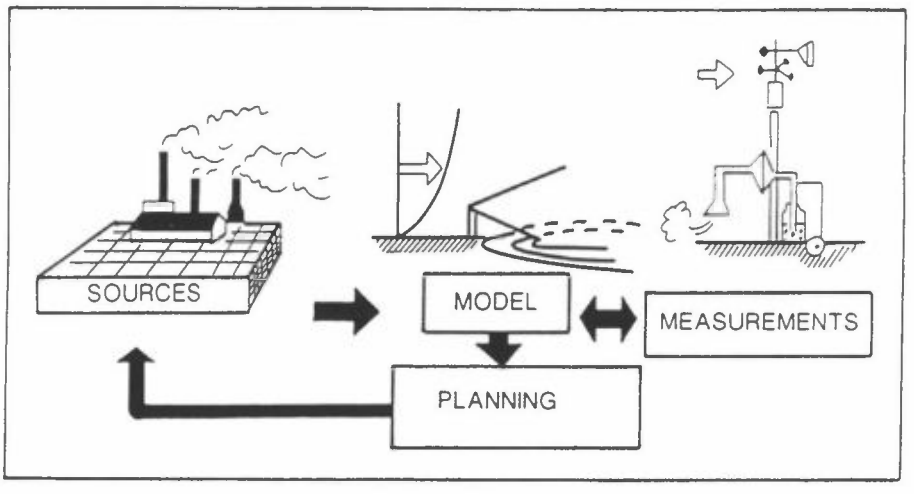


Figure 1: Sources and measurements (air quality and meteorology) are combined in models.

The sampling and analysis of air pollutants is of great importance in air pollution control and abatement. It is a logical connection between emission, transmission in the

atmosphere (dispersion, reactions, deposition), emission (air pollution concentrations) and the effects of air pollution.

Before going into the fundamentals of ambient air sampling; site selection, equipment characteristics, sampling requirements etc., we will first try to indicate some of the more typical objectives of ambient air pollution sampling.

2 OBJECTIVES

A general objective for sampling and analysis will be to adequately characterize air pollution for the area of interest, with a minimum expenditure of time and money. The sampling techniques to be used in each case will be dependent upon a complete analysis of the problem. Main objectives might be as listed in the following.

1. Background concentrations measurements.

2. Air quality determination
   - to check air quality standards
   - to monitor current levels
   - to detect individual sources
   - to collect data for land use planning purposes.

3. Observe trends (related to emissions).

4. Develop abatement strategies.

5. Assess effects of air pollution on
   - health, vegetation, building materials and other.

6. Develop warning systems for prevention of undesired air pollution episodes.

7. Research investigation
   - develop and test diffusion models
   - develop analytical intruments.

Relatively simple equipment is usually adequate to determine background levels (for some air pollutants), to check Air Quality Standards or to observe trends, while more complex sampling equipment is necessary for successful and complete determination of regional air quality, operation of warning systems or diffusion modelling.

As we shall see, there is a wide variety requirements for the different sampling systems. Background concentrations equipment for instance might be simple, but need a better resolution and lower detection limit than instruments for air pollution episode control.

3 OPERATION SEQUENCE

Once the objective of air sampling is well defined, a certain operational sequence has to be followed.

A best possible difinition of the air pollution problem together with and analysis of available personnel, budget and equipment represent the basis for decision on the following questions:

- what spatial density of sampling stations is required?

- how many sampling stations are needed?

- where should the stations be located?

- what kind of equipment should be used?

- how many samples are needed, during what period?

- what should be the sampling (averaging) time and frequency?

- what other than air pollution data are needed: meteorology, topography, population density, emissions, effects, etc.?

- what is the best way to obtain the data (configuration of sensors and stations)?

- how shall the data be communicated, processed and used?

The answers to these questions will vary according to the particular need in each case.

4 SAMPLING STATION DENSITY

The number of stations needed to answer the objectives of the air pollution sampling, depends on many factors such as:

- types of data needed
  - mean values
  - frequency distributions
  - geographical distributions

- population density and distribution

- meteorology and climatology of the area

- topography and size of area

- distribution of industrial areas.

A rough indication of the minimum number of sampling stations needed as a function of population density is given in Figure 2 for a typical community air quality network. Automatic continous sampling equipment in general involve fewer stations than an integrating sampling device (24 hr average or more). The selection of sampling time is, as we shall see later, a func-

tion of the air pollutant caracteristics (emission rate, life time) and time specifications of the air quality criteria.

The ability of combining the air quality data with meteorological data through dispersion modelling, also is a very important tool in the design of sampling networks.

If the location of the maximum air pollution area is known from a limited information about the region's meteorology, and the only objective is to check that air quality standards are met, in some cases even one sampling station may be sufficient.

In a topographically complex area with hills, valleys, lakes, mountains etc., there are considerable local spatial and temporal variations of the meteorological parameters, and thus the dispersion conditions. To answer the same questions, more sampling stations are needed in such areas than in flat homogeneous terrain.

Typical for a flat area is also that spaced stations (as proposed by the German Federal regulations or as is the New York City's aerometric network) average out spatial variations and thus can give net results representative for the area as a whole.

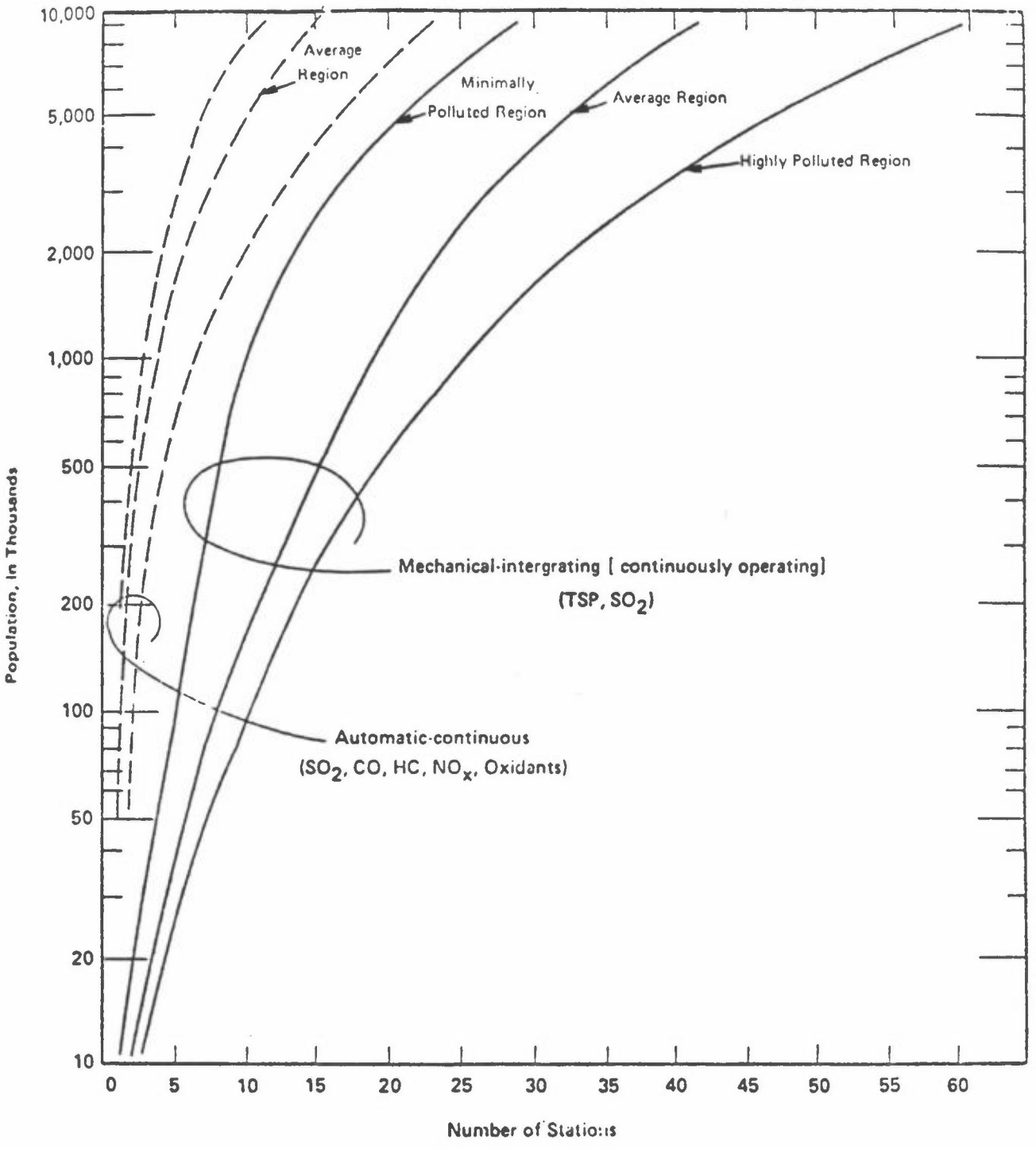


Figure 2: Relationships between minimum number of stations and region population.

5 SAMPLING SITE SELECTION

The location of the individual air samples is also subject to the factors discussed above; meteorology, topography, demography and industry.

In general, an important principle in sampling site selection is to locate the majority of samplers in the most polluted areas, and in areas with the highest population density.

Based on a knowledge of the prevailing meteorological conditions of the area, it is possible to make a rough estimate of a kind of "ground level concentrations distribution", distance to maximum ground level concentration for a single source and the expected level of air pollution for different averaging times.

We shall not go into the diffusion modelling, which is discussed in an earlier lecture but merely show some practical examples of how this theory can be used in sampling site selection, when meteorological information is available.

Figure 3 show the distance to and the value of the maximum ground level concentration (Cu/Q) for an emission Q from a single stack of different plume heights (H_{eff}) under different atmospheric stability conditions and wind speeds (u). From this nomogram it is possible to get a feeling of how far from a single stack one will find the maximum contribution from this source. The overall one hour average ground level concentration at this distance can be estimated from $C=A \cdot Q/u$.

The location of air samplers is also subject to the influence of seasonal variations in the atmospheric conditions. Frequency distributions of different combinations of wind directions, wind speed and stability together with emission data are input to a simple dispersion model, which again give annual or seasonal concentration distributions as output. These distributions represent a valuable background in the planning

of air sampling stations in general. Also when it comes to explaining and interpreting air quality data dispersion model accessability is of great importance.

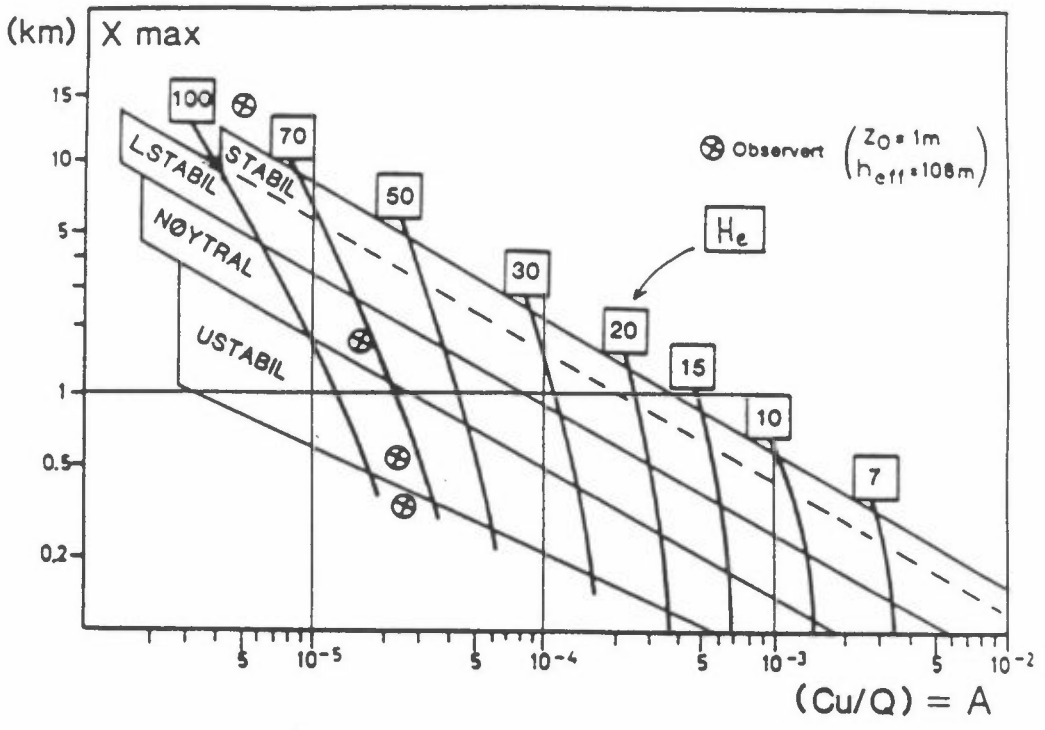


Figure 3: Distance to the maximum ground level concentration (Cu/Q) as a function of stability and effective source height (He). Concentration C = AQ/u, where A can be found on abscissa, Q is release rate (µg/s) and u= wind speed (m/s).

6 LOCATION OF INDIVIDUAL SAMPLERS

When discussing the exact location of each individual sampler, it is essential that the data are representative for the location without undue influence from the immediate surroundings.

A few generel guidelines are summarized as follows:

1. All stations should be placed at the same height above ground level.

2. Constraints to airflow from any direction should be avoided by placing intake probes at least 3 meters from buildings or other obstructions.
3. The surrounding area should be free from local emission sources.

In residental areas an intake elevation of 2 to 6 meters is suggested as the most suitable.

When locating the sampler intake on a building, one should be aware of the characteristic air flow around the building. Emissions from the roof can easily be captured by the turbulent wake at the leeward side of the building and brought to the sampler intake. The height of the emissions above the roof has to be examined carefully before location. Trees surrounding the sampler might also influence the representativity of the data. A tree acts as a filter or a "trap" to some pollutants, some of which are washed off again during precipitation.

7 SAMPLING TIME AND FREQUENCY

The sampling time, during which a discrete sample is collected, or a continuous record is integrated might vary from instantaneous to long time, yielding annual average values. It is important to specify the sampling time whenever air pollution concentrations are quoted. The selection of sampling time and frequency is depending on:

- emission characteristics
- life time of the specific air pollutant of interest
- the type of effect on health, vegetation and materials from the specific air pollutant (acute or integrated)
- the resolution of meteorological data
- governmental regulations or the air quality standard's specifications of averaging time.

It is for instance inadequate to observe monthly average air concentrations to detect sources with a typical diurnal

variation (traffic emissions), or emissions which occure at intervals as puffs with short duration.

On the other hand it is meaningless to use short sampling times for lead or heavy metal particulates with biological half time of 6 months or more, when the purpose of the survey is to determine health effects. In this case monthly means should be sufficient.

To further demonstrate how the effect of air pollution is a function of both concentration and time, it can be mentioned that damage to crops from oxidants may be significant for exposures of 8 hrs or more, while odour can be detected if the threshold is exceeded for as short a time as 1 sec.

The choice of sampling time will always be influenced by the requirements of the objective, by the instrument available, the amount of data needed and by the importance of correlating the data to meteorological measurements.

Air Quality Standards often specify averaging time and principle of detection for the air pollutants in question.

It is always possible to compute averages with data taken at intervals smaller than the averaging period, but the converse is only true if the statistical frequency distribution is known. It is in this connection worth mentioning R. Larsen's statistical model for the frequency distributions, based upon air quality data from six major US cities. He states that common air pollutants (as CO, NO_x, SO_2, hydrocarbons and oxidants) have the following caracteristics:

1. The concentration is log-normally distributed.
2. The medium values is proportional to the averaging time to an exponent and plots a straight line on log paper.

This links all averaging times by an equation.

8 THE SAMPLING SYSTEM

The determination of pollutant concentration involves four steps as shown in Figure 4; and inlet system to bring air to a collection device where the pollution is measured or prepared for analysis, an air flow meter where the volume of air is measured and controlled at a constant rate and an air mover which draws air through the system.

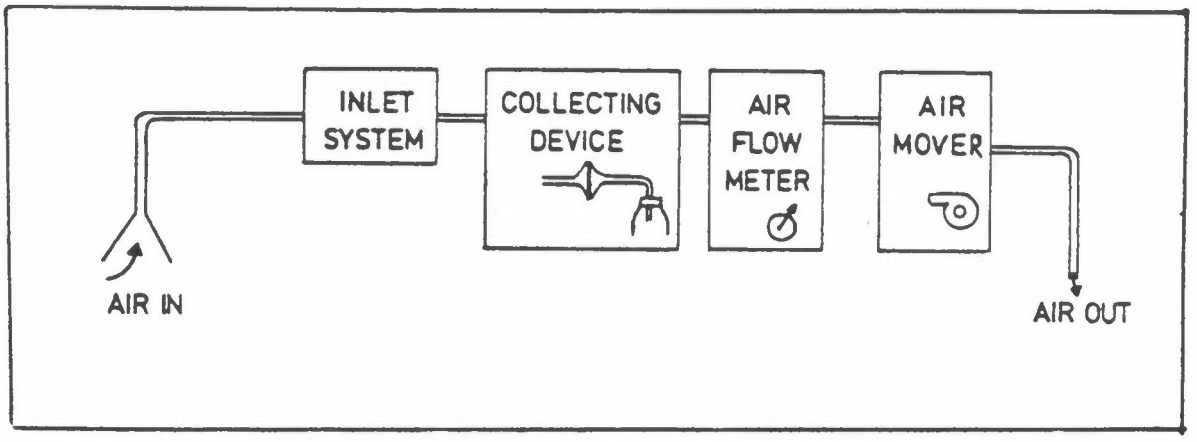


Figure 4: A typical ambient air inlet system.

The inlet system must be clean and made of a material that does not react with the air pollutants. Glass is often preferred. With long inlet systems the time required for a volume of air to reach the collection device must be considered. In addition to time lag, the problem of reaction between the various pollutant with each other during the transfer may arise, due to for instance a higher temperature inside the sampling tube than ambient air. This is particulartly so when sampling nitrogen oxides and ozon. In such cases a high flow system should be considered to reduce or minimize the time lag.

The methods of collecting gases and particulate matter include:
- adsorption

- absorption
- freeze-out
- impingement
- thermal and electrostatic precipitation
- direct measurement
- mechanical filtration.

The collection device is based on discrete sampling periods, semicontinuous or continuous sampling coupled to a recorder or a computer network.

The most commonly used device has been the bubbler, often together with a filtration system. A chemical solution is used to stabilize the pollutant for subsequent analysis with minimum interference by other pollutants.

Adsorption is a convenient method for collecting gases. Activated carbon is the most common adsorbent, used for instance for collecting active hydrocarbons.

To determine the pollutant concentration, it is necessary to measure the air volume sampled, the gas flow rate or the total gas volume sampled. The gas flow rate or the total gas volume integrated over the sampling period may be determined using gas flow meters, rotameters, anemometers or liquid burettes. Temperature and pressure corrections are taken to convert the air volume to standard conditions.

The air mover may be an electrical or battery-powered pump, a squeeze bulb or a vacuum system.

Different from the typical air sampling system described above is the static samplers. These samplers are for instance, dust fall jars, sticky paper, rubber strips, fabric dye, lime paper, lead perioxide candles or metal plates. The interpreting of such data are difficult. Data from different areas are not directly comparable, due to differences in humidity, radiation and external parameters other than air pollution. However,

passive samplers for SO_2, NO_2 and NH_3 have recently been developed, and calibrated and have proven valuable addition to integrated sampling.

9 SAMPLING SYSTEM SELECTION

Methods and instruments for measuring air pollutants must be carefully selected, evaluated and standardized. Several factors must be considered. The sampling system must be:

- specific i.e. respond to the pollutant of interest in the presence of other substances
- sensitive and range from the lowest to the highest concentration expected
- stable i.e. remain unaltered during the sampling interval between sampling and analysis
- precise, accurate and representative for the true pollutant concentration in the atmosphere where the sample is obtained
- adequate for the sampling time required
- reliable and feasible relative to man power resources, maintenance cost and needs.

For continuous, automatic monitoring instruments further requirements must be considered:

- zero drift and calibration (at least for a few days to ensure reliable data)
- response time short enough to record accurately rapid changes in pollution concentration
- ambient temperature and humidity shall not influence the concentration measurements
- maintenance time and cost should allow instruments to operate continuously over long periods with minimum downtime
- data output should be considered in relation to computer capacity or reading and processing.

If one consider the typical air concentrations of some pollu-

tants of interest in air pollution studies, it is seen from Table 1 that as we go from background to urban atmosphere, the concentration for the most common pollutants increase roughly by a factor 1000, in the next step from urban to emission we see another factor of about 1000. Few techniques or instruments

Table 1: Typical concentrations of pollutants in samples of interest in air pollution.

Pollutant	Background	Urban ambient	Stack effluents	Auto emission
CO	0.1 ppm	5 -10 ppm	2.000-10.000 ppm	1-4 %
SO_2	0.2 ppb	0.02- 2 ppm	500- 3.500 ppm	50-100 ppm
NO_x	0.2- 5 ppb	0.2 - 1.0 ppm	1.500- 2.500 ppm	1.500 ppm
O_3	10 ppb	0.1 - 0.5 ppm	-	-
Suspended particulates	10 $\mu g/m^3$	60 $\mu g/m^3$	35 x 10^6 $\mu g/m^3$	
Methane	1.5 ppm	1 -10 ppm		
VOC	< ppb	ppb - ppm	-	1.000 ppm

are capable of measuring the total range of 10^6 ppm. Also the sampling conditions (temperature, humidity, interferring substances etc.) may differ greatly from ambient to emission sampling system is thus influenced by the expected concentration level and the sampling conditions. We usually find that instruments, techniques and analytical approaches are designed for application of specific concentration ranges as represented by background levels, ambient urban air and emission concentrations.

10 USE OF AIR QUALITY DATA

10.1 MEASUREMENT EQUIPMENT AND METHODS

Classification of air quality has to rely upon measured data. The quality of data is dependent upon measurement equipment and methods available.

When selecting and using indicators for specifying the levels of air quality, one has to ensure that:

- Sensors are available for the specified pollutant,
- the time resolution is adequate,
- sensor locations are representative for the problem in question,
- the equipment has been proved operative during all conditions relevant,
- simplifications satisfy user qualifications and requirements,
- analytical methods are calibrated and controlled,
- quality assurance routines are implemented.

10.2 AIR POLLUTION MONITORING PROGRAMMES

Air pollution monitoring programmes are being conducted at different scales in most countries. These programmes include:

- Surveilling impact from local industry,
- local community or urban air pollution monitoring,
- national surveillance for urban and suburban areas,
- national monitoring in remote background areas,
- international programmes for urban and rural areas,
- international programmes for regional and long range transport of air pollutants,
- national and international programmes for global air pollution studies.

Some of these programmes are linked to air pollution transport and dispersion models where local, regional and global meteorological and climatological data together with emission inventories represent the input. The models can produce concentration distributions on the different scales.

The air pollutants considered in each of these programmes have been selected dependent upon the problem that is being addressed.

10.3 URBAN, RESIDENTIAL AND INDUSTRIAL AREAS

In the monitoring programmes conducted in cities, residential areas and in industrial areas, five air pollutants have been extensively studied. These pollutants are usually emitted in large quantities and they are known to cause health effects at commonly occurring levels. The pollutants are:

- Sulphur dioxide (SO_2)
- Suspended particulate matter (SPM)
- Nitrogen dioxide (NO_2)
- Carbon monoxide (CO)
- Lead (Pb)

The main source of these pollutants is fuel combustion both by home heating, industry and vehicles. Several indicators have been used for particles in the air (SPM). The simplest one to measure has been black smoke or soot by reflectrometic methods (OECD). At present particles are often measured by two-stage filter samplers or impactors deviding the particles into sizes with diameter less than 10 micrometre (μm) (PM 10) (inhalable particles) or less than 2.5 μm (respirable particles).

The representativity of sampling site locations are in some cases controlled by the use of source oriented dispersion models or source receptor models. The possibility of classifying the air pollution situation increases considerably by the additional use of models.

In rural and background areas as well as for global air pollution problems components, sampling times and frequencies as well as requirements for detection levels and accuracies are different from those in urban areas.

11 AIR POLLUTION IMPACT

The most important requirement for the selection of air quality indicators should be a consideration of potential effects of the various air pollutants on:

- health and the well being of humans,
- flora and fauna,
- materials (building stock and monuments)

The time scale is again of great importance. Short term acute toxicity represented by very high concentrations over short periods of time, often linked to accidental releases or conditions leading to air pollution episodes, acts differently from long term chronic exposure. The latter type is often connected to deposition, uptake and intake over time. Different pollutants have to be considered on the different scales in time and space.

11.1 HUMAN HEALTH

Human exposure to air pollution usually concerns a mixture of different pollutants from different sources. It has thus been difficult to establish reliable dose/response relationships from actual field data. Interesting results have resently been presented from a study on the health impact of traffic air pollution in Norway.

From more than one thousand persons followed through diaries and questionnaires the statistical analyses indicated that various symptoms of health and well being were correlated to exposures to traffic pollution equivalent to NO_2 levels even less than 200 $\mu g/m^3$ as a one hour average. Headaces, coughing, eye irritations, throat problems and depression were some of the symptoms asked for.

The best available background material for evaluation of health impacts is the US-EPA criteria documents and the air quality

guidelines (AQG) for Europe (WHO, 1987). This AQG is formulated to ensure that populations exposed to concentrations lower than the guideline values should not suffer harmful effects. In cases where the guideline for a pollutant is exceeded, the probability of harmful effects will increase.

The WHO guideline values for SO_2 and particulate matter are presented in Figure 5.

There are also several national standards or proposed guidelines available related to human health impact. Some of these are also under revision.

11.2 FLORA AND FAUNA

The air quality guidelines should also have been extended to represent the potential impact on vegetation and animals (see Figure 5 b)).

Studies of plant damage and air pollution impact on plant growth have been performed for several individual air pollutants and for air pollution mixtures. In the discussion of specific indicators we will have to take into consideration recent scientific results on plant damage.

Also the consideration of critical loads should be taken into account. The critial load values is defined as a quantitative estimate of the exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge.

The critical load for a given area depends strongly upon geology, vegetation and soil properties. It might thus be difficult to generalize. However, for acid deposition compounds and ozone a considerable step forward has been made during the last two years. A map for the exceedance of critical loads for the fresh water system in Southern Norway was presented in 1990.

a) Guideline values for combined exposure to sulfur dioxide and particulate matter[a]

	Averaging time	Sulfur dioxide	Reflectance assessment: black smoke[b]	Gravimetic assessment	
				Total suspended particulates (TSP)[c]	Thoracic particles (TP)[d]
		($\mu g/m^3$)	($\mu g/m^3$)	($\mu g/m^3$)	($\mu g/m^3$)
Short term	24 hours	125	125	120[e]	70[e]
Long term	1 year	50	50	—	—

[a] No direct comparisons can be made between values for particulate matter in the right- and left-hand sections of this table, since both the health indicators and the measurement methods differ. While numerically TSP/TP values are generally greater than those of black smoke, there is no consistent relationship between them, the ratio of one to the other varying widely from time to time and place to place, depending on the nature of the sources.

[b] Nominal $\mu g/m^3$ units, assessed by reflectance. Application of the black smoke value is recommended only in areas where coal smoke from domestic fires is the dominant component of the particulates. It does not necessarily apply where diesel smoke is an important contributor.

[c] TSP measurement by high volume sampler, without any size selection.

[d] TP equivalent values as for a sampler with ISO-TP characteristics (having 50% cut-off point at 10 μm), estimated from TSP values using site-specific TSP/ISO-TP ratios.

[e] Values to be regarded as tentative at this stage, being based on a single study (involving sulfur dioxide exposure also).

b) Guideline values for individual substances based on effects on terrestrial vegetation

Substance	Guideline value	Averaging time	Remarks
Nitrogen dioxide	95 $\mu g/m^3$ 30 $\mu g/m^3$	4 hours 1 year	In the presence of SO_2 and O_3 levels which are not higher than 30 $\mu g/m^3$ (arithmetic annual average) and 60 $\mu g/m^3$ (average during growing season), respectively
Total nitrogen deposition	3 g/m^2	1 year	Sensitive ecosystems are endangered above this level
Sulfur dioxide	30 $\mu g/m^3$ 100 $\mu g/m^3$	1 year 24 hours	Insufficient protection in the case of extreme climatic and topographic conditions
Ozone	200 $\mu g/m^3$ 65 $\mu g/m^3$ 60 $\mu g/m^3$	1 hour 24 hours averaged over growing season	
Peroxyacetylnitrate	300 $\mu g/m^3$ 80 $\mu g/m^3$	1 hour 8 hours	

Figure 5: WHO guideline values
a) for protection of human health
b) based on effects on terrestrial vegetation.

The impact on animals is often linked to uptake, intake and food chain processes. Effects of specific toxic substances, especially some toxic heavy metals, long lived chlorinated compounds, organic compounds and fluorides might be of interest. None of these compounds have, however, been included in the list of AQI in this paper. For further evaluation some of them might be of importance.

11.3 BUILDING MATERIALS

The concern for our cultural heritage and for the general life time of building and constructions have increased during the last few years. Considerations for this part of our environment and for the cost of restoration and rebuilding, should be built into the air quality levels when considering air pollution indicators.

As for human health the impact is usually a result of mixtures of compounds included air pollution, climate, weathering, wind, humidity, temperature, errosion, freezing, etc.

Dose response relationships have been established for a few specific air pollutants. For SO_2 these data have been used in cost/benefit analyses for sulphur-reduction measures linked to the use of fuel oil in Europe.

12 AIR QUALITY INDICATORS FOR URBAN AIR POLLUTION

A large set of air quality indicators (AQI) can be proposed for different purposes and for application on different scales. The indicators to be selected for future use have to be linked to measurement methods (sensors and analyses) and to future monitoring systems. This is of importance in the development of control programmes and for international harmonization of monitoring and surveillance programmes.

We do not believe that the establishment of one air quality index, in which several air pollutants are merged into one index value, will be to the advantage for the users. This one number might mask variations and trends in single component pollutants which can be significant to air pollution impacts. The following section will therefore outline a set of single parameters that can be used as air quality indicators for urban air pollution problems.

Table 2: A set of parameters relevant for urban air pollution problem.

Area	Compound	Effect	Averaging time *)
Urban	SO_2	Health	1 h, 24 h, 6 months
	NO_2	"	1 h, 24 h
	CO	"	1 h, 8 h
	Black smoke	"	24 h
	PM10	"	24 h
	O_3	"	1 h
	Heavy metals	"	24 h 1 month
	Dust fall	Estetics	1 month

The selection of parameters should be based upon an analysis of the specific problems in the area which is to be considered. The selection has to be based upon the type of emissions, available measurement data and criteria for air pollution impact on health, vegetation or materials. The averaging times to be considered should be in accordance to those given by the air quality standards, and should also be relevant to potential impacts and effects.

Examples of AQIs to be used to assess the air quality in urban areas is presented below in priority sequence. These indicators should be independent upon the measurement methods. However, it is important to bear in mind the data collection requirements.

12.1 FIRST PRIORITY AQI

SO_2, measured at locations representative for one-kilometre scale pollution levels with continuous monitors. 1 h averages should be recorded in the data base for estimates of 24 h- and 6 months averages.

NO_2, measured at locations in streets, along roads and on kilometre scale, with continuous monitors. 1 h averages should be recorded for estimates of 24 h averages. (It might be useful to estimate NO_2/NO_x ratios if NO_x data are available.)

CO, measured in streets and along roads, with continuous monitors. 1 h averages should be recorded, and running 8 h averages should be estimated.

PM10 measured on locations exposed to long term impact with two stage filter (impactor) samplers. Particle diametre cut off should be 10 µm and 2,5 µm. 24 h averages should be collected.

12.2 SECOND PRIORITY AQI

Black smoke measured with simple filter samplers based upon 24 h averages.

SO_2 at locations as above, but with 24 h average samplers based upon impregnated filter methods or wet absorption.

NO_2 (as for SO_2 above)

O_3 should be measured on a one-hour average basis both for assessment of photochemical smog formation, and as input for describing the oxidation potential in urban areas.

Aerosols at locations exposed for long term impact, preferably with dichotomous high volume filter samplers based upon 24 h average sampling. Filters should be analyzed for relevant heavy metals, e.g. Pb, As, Cd, Cr. The type and amount of metals will be dependent upon purpose and use. For source receptor modelling a large amount of metals should be analysed. For assessment purposes monthly average values should be adequate.

Dust fall at several locations to measure large falling particles in standard dustfall gauges, for assessment of estetic impact.

13 DATA ANALYSES

Standardized statistical analyses should be performed to assess air quality trends, changes in emissions or impact from spcified sources. The severity of the air pollution problem or the air quality should be specified relative to air quality standards (AQS) or guidelines or preset levels of classification (e.g. good, moderate, unhealthy, hazardous ....).

The number of hours and days, or percentage of time when the air pollution concentrations have exceeded AQS should be presented. This will also need minimum requirements of the data base completeness. Long term averages (annual or seasonal) should be presented relative to AQS. In the Norwegian surveillance programme the winter average values of SO_2 and NO_2 are presented on maps in percent of the national air quality guideline values.

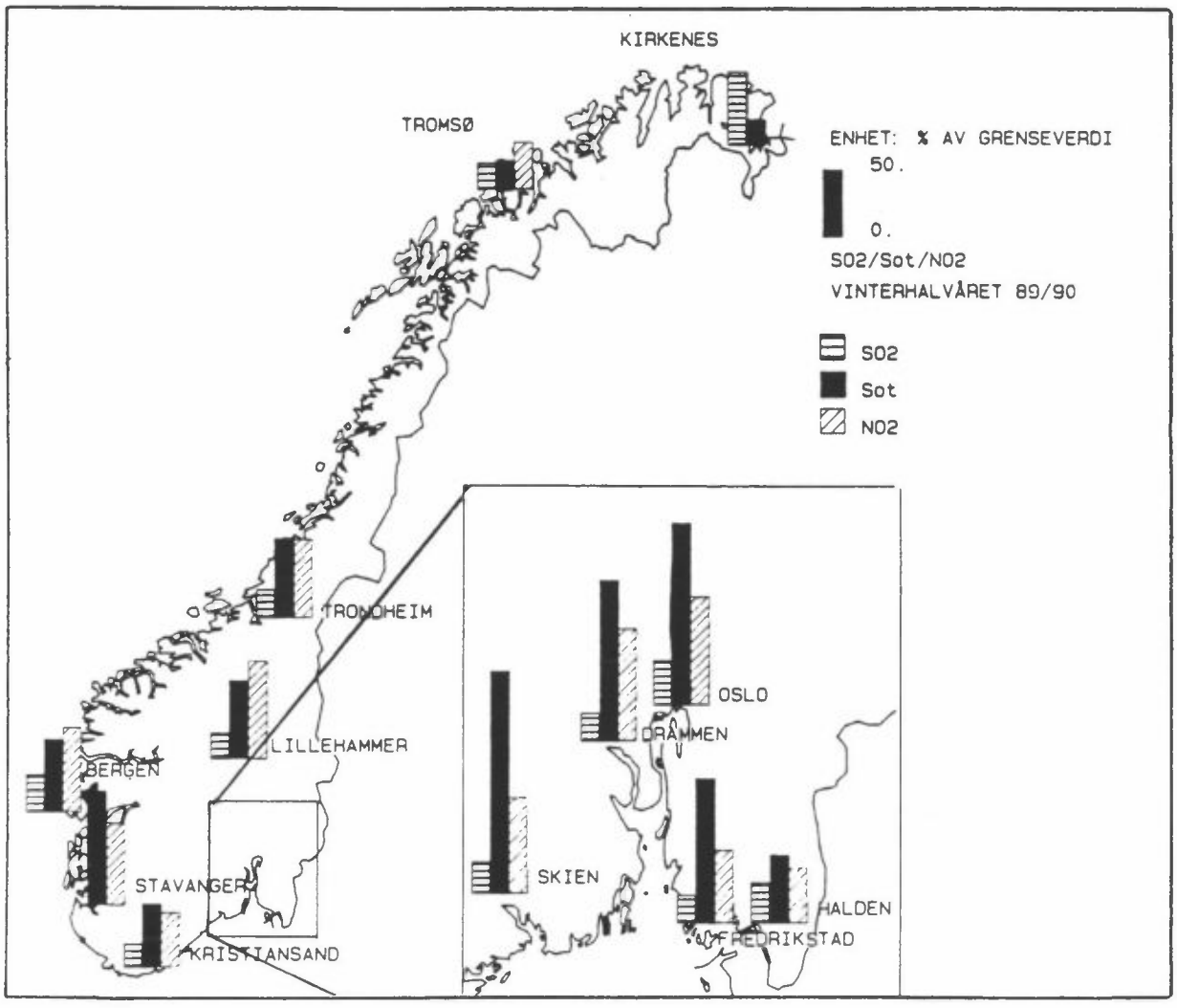


Figure 6: Consentrations (6 month average) as a percentage of the Norwegian air quality guideline values for SO_2, NO_2 and soot.

14 CLASSIFICATION OF AIR QUALITY

The main basis for the classification schemes applied in Norway has been the proposed air quality guidelines for Norway and the Air Quality Guidelines for Europe (WMO, 1987). The Norwegian guidelines are presented in Table 3.

Table 3: Air quality guidelines proposed by a committee established by the Norwegian State Control Authorities (SFT) in 1978.

Pollutant	Measurement unit/method	Effect on	Averaging time				
			1 h	8 h	24 h	30 d	6 months
Sulphur dioxide (SO_2)[a]	$\mu g/m^3$	Health			100-150		40-60
Suspended particles[a]	"				100-150		40-60
Sulphur dioxide (SO_2)	"	Vegetation	150		50		25
Nitrogen dioxide (NO_2)	$\mu g/m^3$	Health	200-350		100-150		75
Carbon monoxide (CO)	mg/m^3	Health	25	10			
Photochemical oxidants	$\mu g/m^3$ The ozone content measured	Health	100-200				
" "		Vegetation	200				
Fluorides [b]	$\mu g\ F/m^3$	Health			25		10
" [b]	" "	Animals				0,2-0,4[d]	
" [c]	" "	Vegetation			1,0		0,3

a) Assuming that both compounds are existing simultaneous (synergistic effects)
b) Total fluorides
c) Only gaseous fluorides
d) Based upon deposition to pasture (grass), and a maximum content of fluor of 30 mg per kg dry grass.

Impact on human health, animals and vegetation have been considered for the establishment of the Norwegian guidelines. The guidelines are at present under revision.

The data background for these analyses has been the measurements performed by NILU for the State Pollution Control Authorities (SFT) as part of the national air quality surveillance programme. Statistics on these data are presented in quarterly and annual reports. Air quality trends and frequency of occurrance of concentrations exceeding AQG are presented in these reports. Examples of such presentations are presented in Figure 7.

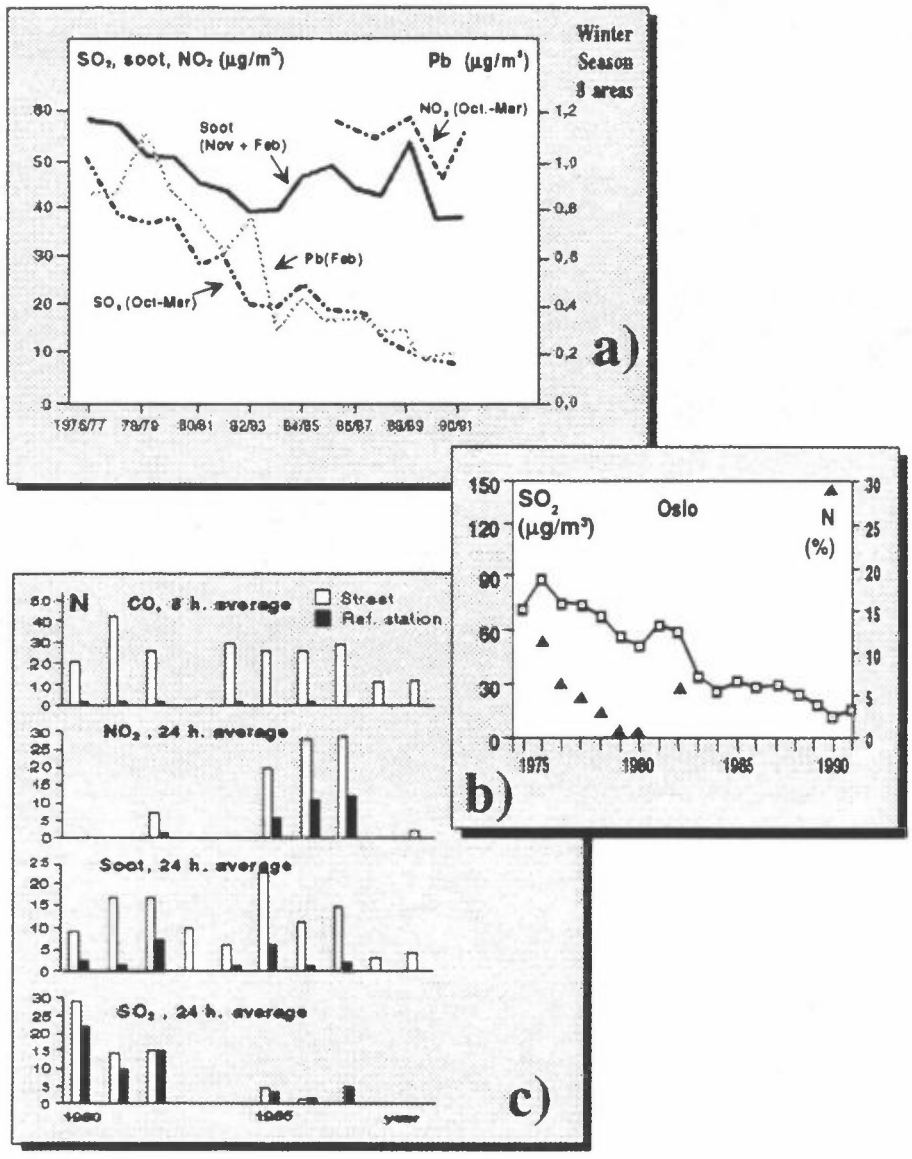


Figure 7: Examples of presentation of data from the Norwegian air quality surveillance programme:
a) Trends of 6 months winter average concentrations from 8 selected urban areas for soot, NO_2, SO_2 and lead, 1976-89.
b) Trends and frequency of exceedance of AQG for SO_2 in Oslo (1973-90).
c) Number of days with exceedance of AQG at two sites in Oslo for CO (8 h), NO_2, soot and SO_2 (24 h) (1980-89).

The classification was performed in two steps. In 1986 54 urban and industrial areas were analyzed. The last study carried out in 1989 concidered three air pollution compounds and ten city areas. The air pollutants included SO_2, soot (black smoke) and NO_2. The classifying criteria were based upon the proposed Norwegian air quality guidelines.

Possible atmospheric corrosion problems and potential vegetation damages were taken care of by lowering the 6 month average SO_2 criteria below those related to health.

Also other trace elements and organic carcenogenic air pollutants linked to high concentrations of soot have been taken into account by lowering the 6 month average soot criterium to 20 $\mu g/m^3$.

The classifying criteria are given in Table 4.

Table 4: Classification criteria for Norwegian urban areas.

Compound	Effect on	Average time	Criterium
SO_2	Health Materials Vegetation	24 h 6 months	100 $\mu g/m^3$ 20 "
Soot	Health	24 h 6 months "	100 $\mu g/m^3$ 40 " 1) 20 " 2)
NO_2	Health	1 h 24 h 6 months	200 $\mu g/m^3$ 100 " 75 "

1) Upper limit, 2) Lower limit

The criteria are considered exceeded if <u>one</u> of the limits have been exceeded. In this classification scheme the ten cities were divided into two categories:

a) "moderate polluted" (criteria not exceeded)
b) "polluted" (criteria exceeded)

The two classes were presented for each individual compound. In cases where measurement data can be combined with emission inventories and simple air pollution model estimates, it is possible to indicate the area exposed to pollution exceeding the classifying criteria. An example from Oslo is shown in Figure 8.

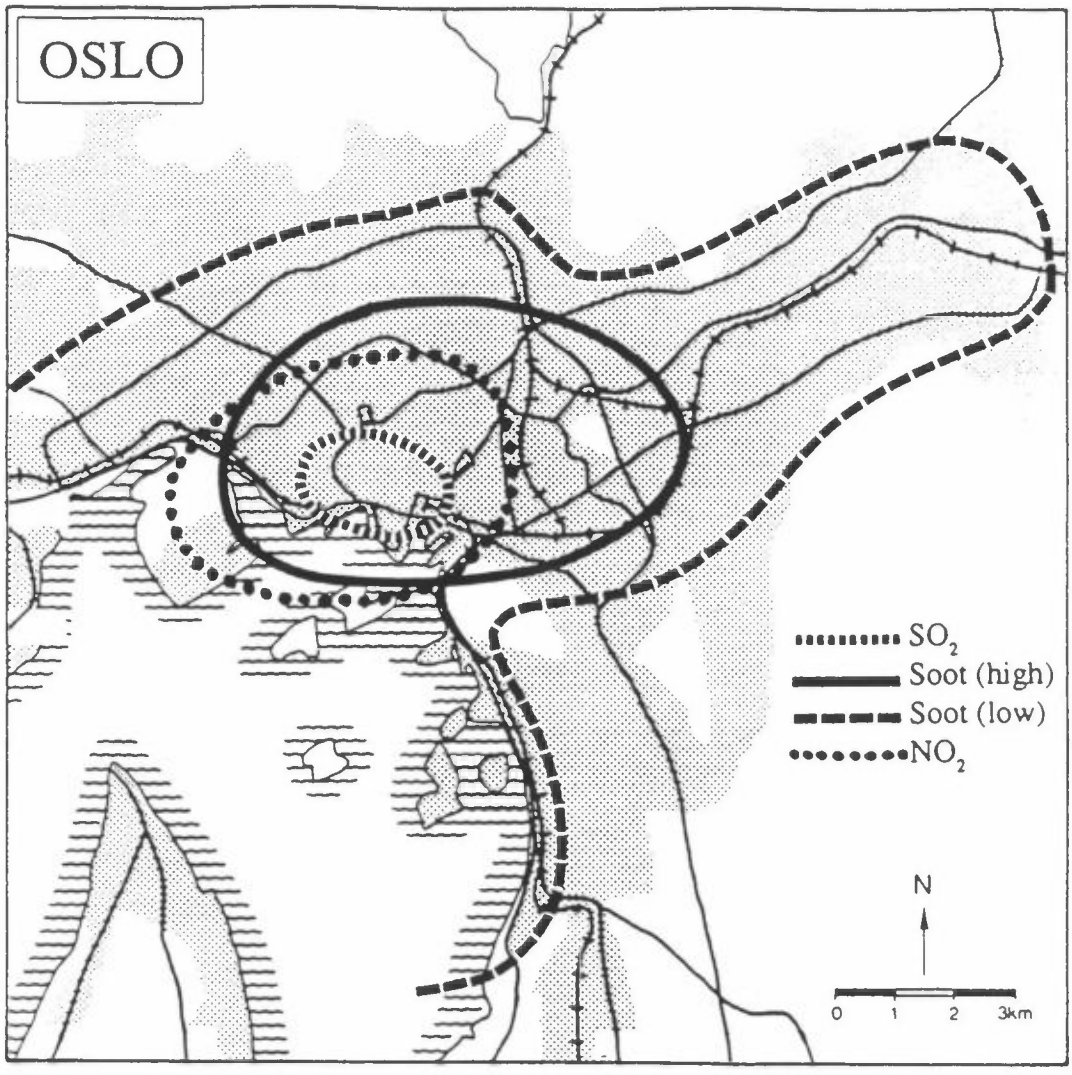


Figure 8: Air quality classification of SO_2, soot, and NO_2 in Oslo, Norway. The areas within lines are exposed to air pollutants exceeding the criteria in Table 2.

In areas where the criteria were exceeded, an estimate of the number of people exposed was also presented. In the example for Oslo about 15.000 persons were exposed to SO_2 concentrations exceeding the criteria. In this way it has been possible to define one simple number which gives a comparable indication for the air quality impact in the different urban areas in Norway.

The air quality classification performed for urban areas has been used in long term planning. It has also been used for selection of areas where more detailed strategy plans are being developed.

The results have been made available to local authorities who have been made aware of their "problems". However, only in very few occations have they directly applied the classification results for planning purposes. The results have, however, in some cases been used for designing monitoring programmes.

15 CRITICAL LOADS/CRITICAL LEVELS

Recently air pollution impact on the environment has been discussed relative to critical load values.

The international accepted definition of critical loads/levels are:

"A quantitative estimate of and exposure to one or more pollutants below which significant harmful effects on specific sensitive elements do not occur according to present knowledge."

This definition implies that pollution above the critical load/level will lead to permanent damage to a given ecosystem.

Research activities have set the limits of critical loads. These loads are related to ecosystem sensitivity. The highest politically acceptable load of a pollutant is the "target load". The target load can be set at, above or below the critical load. If the target load is set above the critical load, one accepts that the most sensitive ecosystems will be nega-

tively affected. If it is set below, a safety margin is included.

The critical level values have often been presented as air quality criteria or air quality guidelines. Air quality guidelines as given for the protection of human health by the World Health Organization (WHO, 1987) and for protection of forests by the International Union of Forest Research organization (IUFRO, 1978) is presented in Table 5.

Table 5: Examples of proposed air quality guidelines for protection of health and forest as given by WHO (1987) and IUFRO (1978).

Protection of	Conc. ($\mu g/m^3$)	Average time	References
Health	30 350	year 1 h	WHO, 1987 WHO, 1987
Forests	25 50 150	6 months 24 h 1 h	IUFRO, 1978 IUFRO, 1978 IUFRO, 1978

Such values of critical levels have been used to estimate areas where seasonal or monthly averages of air pollutants have exceeded these given values as shown in Figure 9.

Figure 9: Areas of seasonal average SO_2 concentrations above 25 $\mu g/m^3$ (1990/91).

16 SPECIFIC FIELD EXPERIMENTS

Field experiments might be carried out for various reasons. The experience at NILU are:

- tracer experiments to study emission of diffuse leakages, dispersion, ventilation, wake effects, topographical difficulties etc.

- detailed studies of concentration distributions in space and time

- local investigations of dispersion meteorology using:
  - multiple pilot sensors
  - balloons (pilot, tetroons, tehthered balloons)
  - remote sensing (lidar, acoustic sounder, etc.)
  - tracers (SF_6, $CBrF_2$, oil fog, particles, etc. ...)
  - camera studies of plumes (time lapse photography)

- sampling of specific sources or source areas combining air quality measurements, tracer gas techniques and meteorological studies.

Tracer experiments have been undertaken for various reasons:

- building wake
- topographical complexities
- diffuse leakages from industrial sources
- quantify individual source impact.

Several aspects have to be considered when designing a tracer gas experiment:

- the releases configuration (location, height, density, etc.)
- number of release points
- the design release rate
- number of samplers
- traverse (or sampler) locations

- coordinate specification (reference)
- meteorological data representativity
- data analysis (in field)

Tracer experiments designet for examining diffuse leakages can only be conducted when the following conditions are fulfilled:

- wind speed should be >3 m/s to create mechanically induced turbulence for tracers to be sufficiently well mixed at the sampling points;
- periods with precipitation should be avoided;
- release time must adjust to wind speed and sampling point distances;
- sampling time must be long enough to avoid short period fluctuations due to atmospheric turbulence;
- sampling point location should assure at least one horizontal cross section of the concentration distribution;
- tracer release points and release rates relative to each other should be located and proportioned to match actual leakages;
- meteorological variables should be continuously recorded.

16.1 EXAMPLE OF EXPERIMENT FOR EMISSION ESTIMATE

The inert tracer gases usually applied in these studies are not depositing on the surface or washed out by precipitation downwind from release. Applying simple proportionality models for estimating leakage rates requires that the air pollutants of interest are dispersed in the same way. Dry weather conditions, strong winds and short transport times should assure that no chemical or physical changes take place.

If the tracers (t) are released from the same point (or area) as the pollutants (p), the ratio of total fluxes downwind (F) will be the same as the ratio between the emissions rates (Q):

$$Q_p / Q_t = F_p / F_t$$

Assuming that the experiments are carried out during high winds with mechanically induced turbulence and good mixing of tracers and pollutants and that there is no significant difference between tracer and pollutant release heights, the emission rate of pollutants (Q_p) can be estimated from the ratio of crosswind integrated concentrations downwind from the source area:

$$Q_p = Q_t \cdot \left(\int_y C_p \, dy / \int_y C_t \, dy\right)$$

It is assumed that the total release rate of tracers is controlled and known (Q_t) and that concentrations of pollutants (C_p) are measured at selected points downwind. These measurements are taken along arcs perpendicular to the wind direction (Figure 10). Tracer concentrations (C_t) are measured at a great number of sampling location with the small NILU-samplers available. Tracers can thus be applied to establish a detailed mapping of the plume.

To verify the emission estimates, concentration measurements should be taken at more than one arc, and preferably during different wind direction. In this way a measure of the overall uncertainty of the emission estimate can be established.

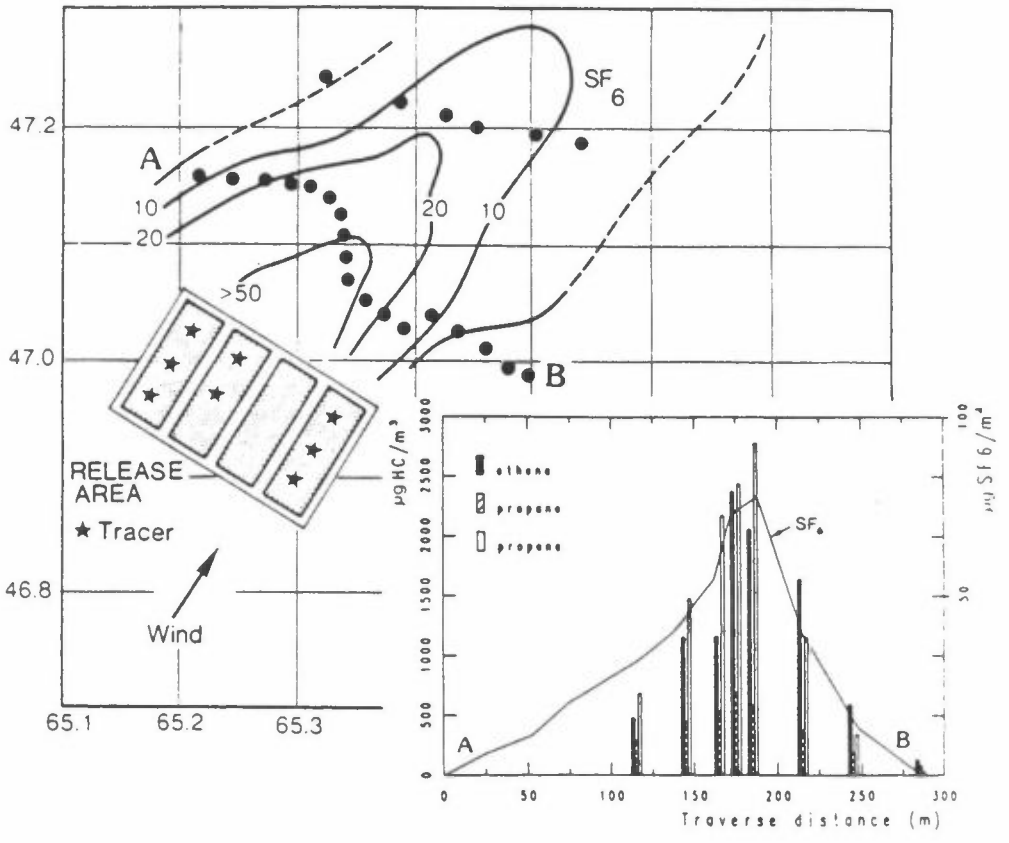


Figure 10: 15 min. average concentrations of SF_6 and hydrocarbons ($\mu g/m^3$) measured downwind from a petrochemical complex.

17 ROAD TRAFFIC AND LOCAL AIR POLLUTION PROBLEMS

The most important problem locally associated with road traffic is the possibility for negative health effects due to high concentrations of CO, NO_2, and particles containing soot and organic compounds.

In many cities road traffic is the dominating source of CO, NO_2, and particles. The concentration in air of these compounds frequently exceeds air quality guidelines, especially during the winter months. This occurs locally in streets and in the

city atmosphere in general.

At street level short term air quality guidelines are exceeded when the annual daily traffic exceeds 5-10 000 cars per day. For congested traffic the air quality guidelines for CO are the first ones to be exceeded. Guidelines for NO_2 and soot are also exceeded, especially when the traffic contains at least 5-10% of diesel trucks.

Air quality guidelines of NO_2 and black smoke (24 h average values) are often exceeded in the city centers, generally due to road traffic emissions. The ozone concentration in the air coming into the city from outside is an important factor for NO_2 formation in the city atmosphere. The long-term development of this regional ozone concentration will determine the future trend in the local NO_2-concentrations, in addition to the local emission reduction which will take place with the introduction of catalyst cars.

The air quality guidelines proposed for Norway related to car exhaust are based on the guidelines proposed by the World Health Organization (WHO). They are as follows:

Compound	AQ guideline	Averaging time
CO	25 mg/m^3	1 hour
	10 mg/m^3	8 hours
NO_2	200-350 µg/m^3	1 hour
	100-150 µg/m^3	24 hours
	75 µg/m^3	6 months
Black smoke	100-150 µg/m^3	24 hours
	40- 60 µg/m^3	6 months

17.1 MEASUREMENTS IN STREETS

Air quality guidelines for car exhaust components include both short term exposure (for instance 1-hourly average values for

CO and NO_2) and long term exposure values (for instance 24-hour average values for NO_2 and black smoke, and 6-monthly average values for NO_2).

Characterization of air pollution due to road traffic requires a measurement program including both continuous monitors and sampling equipment taking integrated samples.

Pollution concentrations due to car exhaust varies in time both due to diurnal traffic variation and to variation in dispersion conditions. Figure 11 shows an example of the extreme variations in hourly concentrations that typically occur in traffic-exposed areas. The example is from curb-side measurements of CO over a 1-month period with and annual daily traffic of about 35 000 cars.

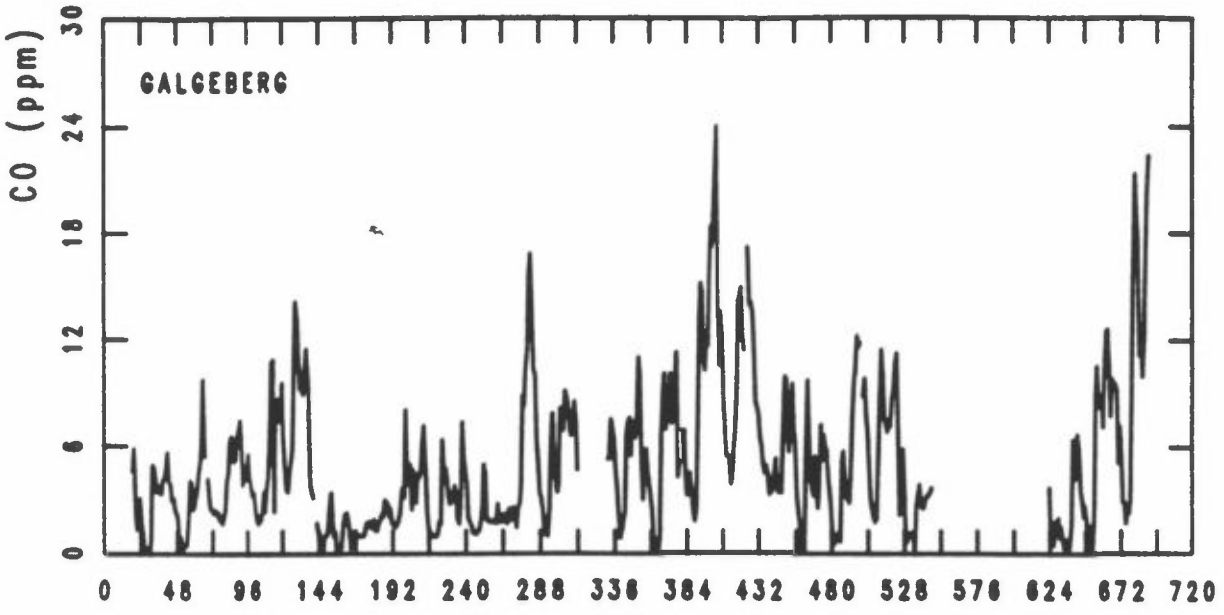


Figure 11: Example of typical pollution concentration variations close to a road. CO measurements (1-hour average values) over a 1-month period (October-November 1987) close to a road in Oslo with about 35 000 cars/day.

Characterizing both maximum and average concentrations requires a rather extended measurement period. Measurement periods shorter than 2-3 months are not recommended, to get a good estimate of maximum short term concentrations. Measurements should be made during the time of the year when poor dispersion conditions are most likely to occur, i.e. during winter conditions.

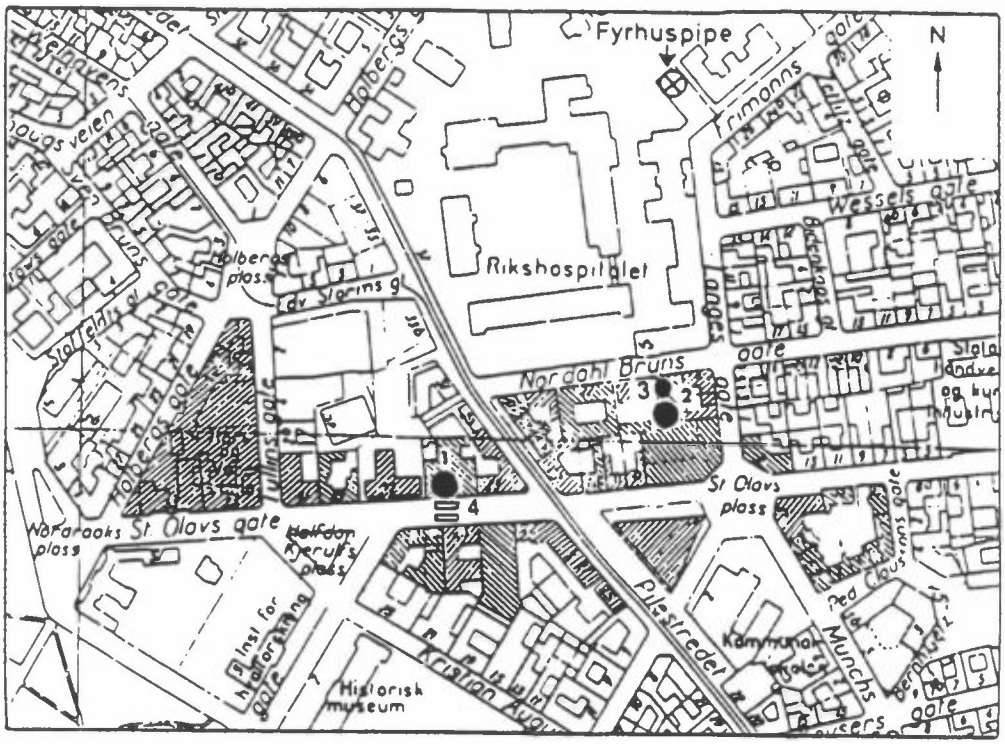
The measurement program for car exhaust pollution in Oslo is described here as an example of a program answering to the following objectives:

- To monitor the trend in car exhaust pollution in highly traffic exposed areas in general, and close to streets in particular.
- To monitor the trend in car exhaust emission factors.

The cost-efficient measurement programme in Oslo is as follows:

- Two pairs of measurement stations are used. A station pair consists of a street station (on sidewalk) and a reference station nearby, which monitors the general air pollution concentrations in the area (see Figure 12).
- One station pair on a street with mainly light duty traffic (gasoline exhaust), and one pair on a street with a large contribution from heavy duty traffic (diesel exhaust).
- Continuous monitors for CO and NO/NO_2 (preferably also O_3).
- Integrating samplers to collect 24-hour samples for analysis of NO_2, SO_2, soot, inhalable particles (PM_{10}), lead, PAH and mutagenicity.
- Traffic analyzer at the street station, collecting hourly data for no. of cars, traffic speed and preferably vehicle type (light duty/heavy duty).
- Wind and temperature measurements (hourly data).

STATION PAIR A. OSLO CENTRE



1. Curbside station
2. Reference station
3. Meteorology station
3. Traffic detectors

STATION PAIR B. DIESEL TRAFFIC

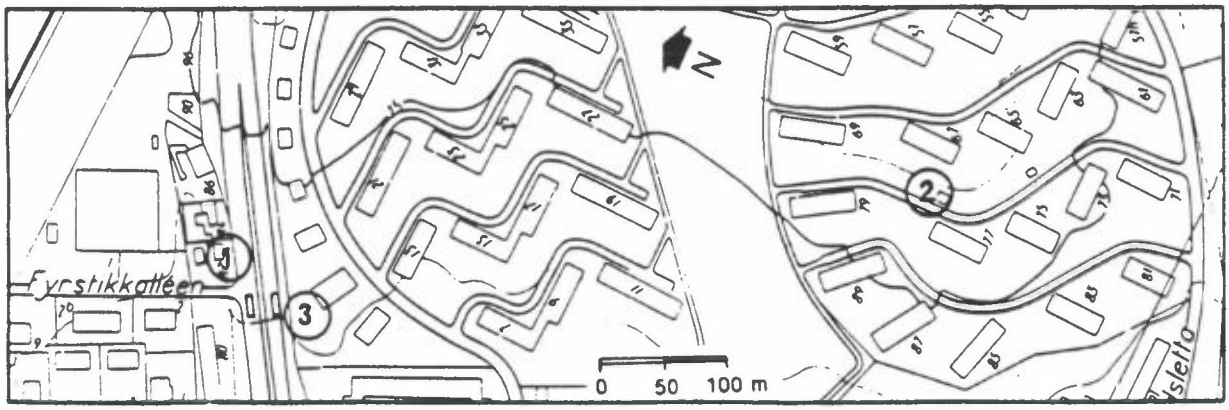


Figure 12: Location of pairs of measurement stations in Oslo, for car exhaust pollution monitoring.

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REFERENCE : O-92014
DATE : MAY 1992

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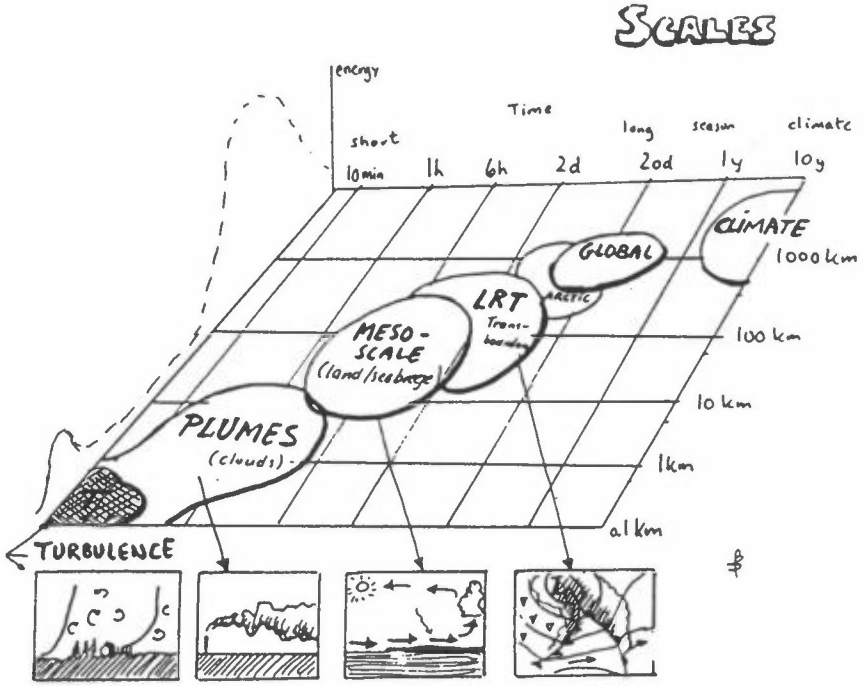
Air Pollution Models

B. Sivertsen



NILU

NORSK INSTITUTT FOR LUFTFORSKNING
Norwegian Institute For Air Research
POSTBOKS 64 — N-2001 LILLESTRØM — NORWAY

AIR POLLUTION MODELS

1 INTRODUCTION

Models used in air pollution studies can be devided into two families of models types:

1. Source oriented models
2. Receptor models

The source oriented models combine information about sources (emission inventories), meteorology and topography to estimate concentrations and concentration distributions.

Receptor models use measured concentrations of various air pollutants over a long time periods and can by statistical analyses identify source impact and different source's contribution to the concentrations measured at specific points. The differences in the two types of models are illustrated in Figure 1.

In the following presentation we will only be dealing with source oriented models. These mathematical models are able to estimate the atmospheres capacity to transport and diffuse gases or aerosols, and is of great importance in evaluating the future impact of planned normal or accidental releases. It is only when the connection between the sources and the air quality has been established by models, that a planning tool is available (Figure 2).

In more details an example of an air quality model established to estimate the contribution to man and the environment from different sources such as; energy, traffic, industry and other sources is shown in Figure 3.

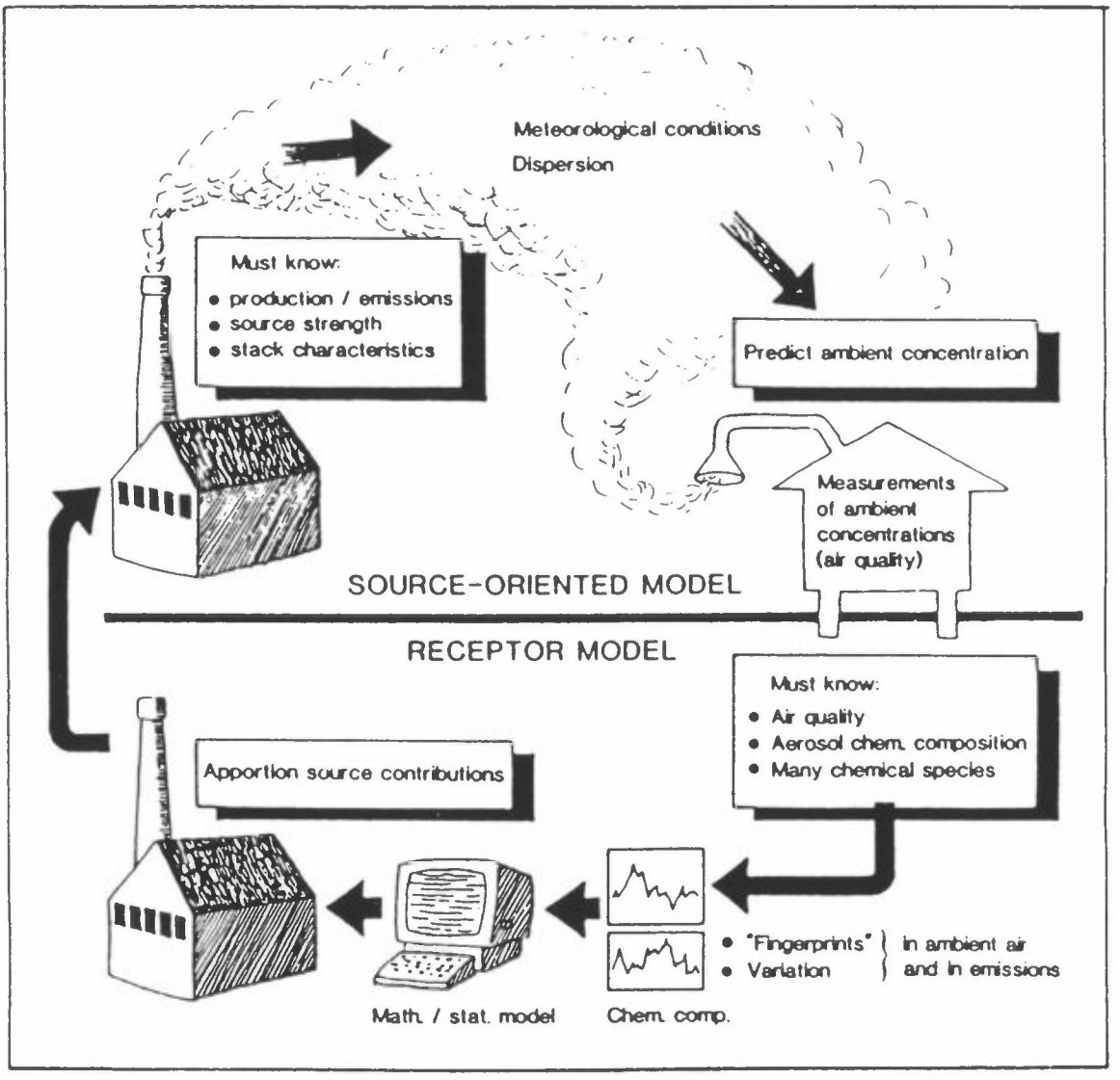


Figure 1: Source oriented and receptor models work from different input data.

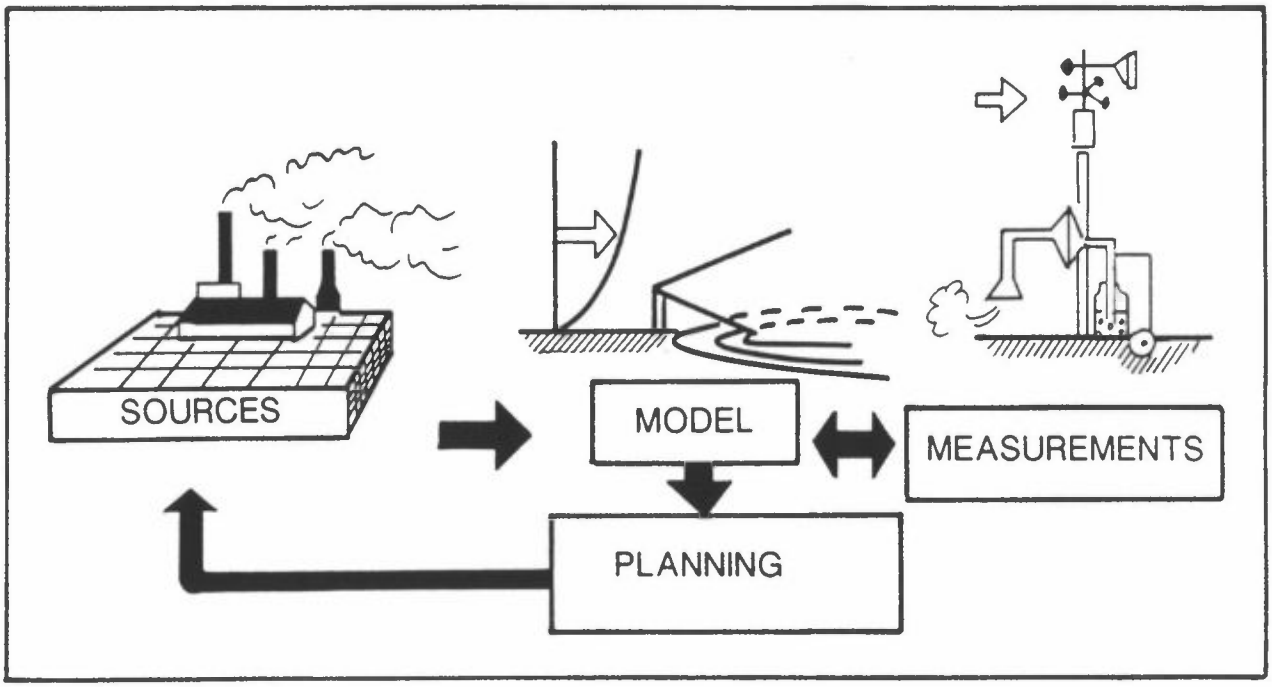


Figure 2: Source oriented models establish the connection between sources and air quality.

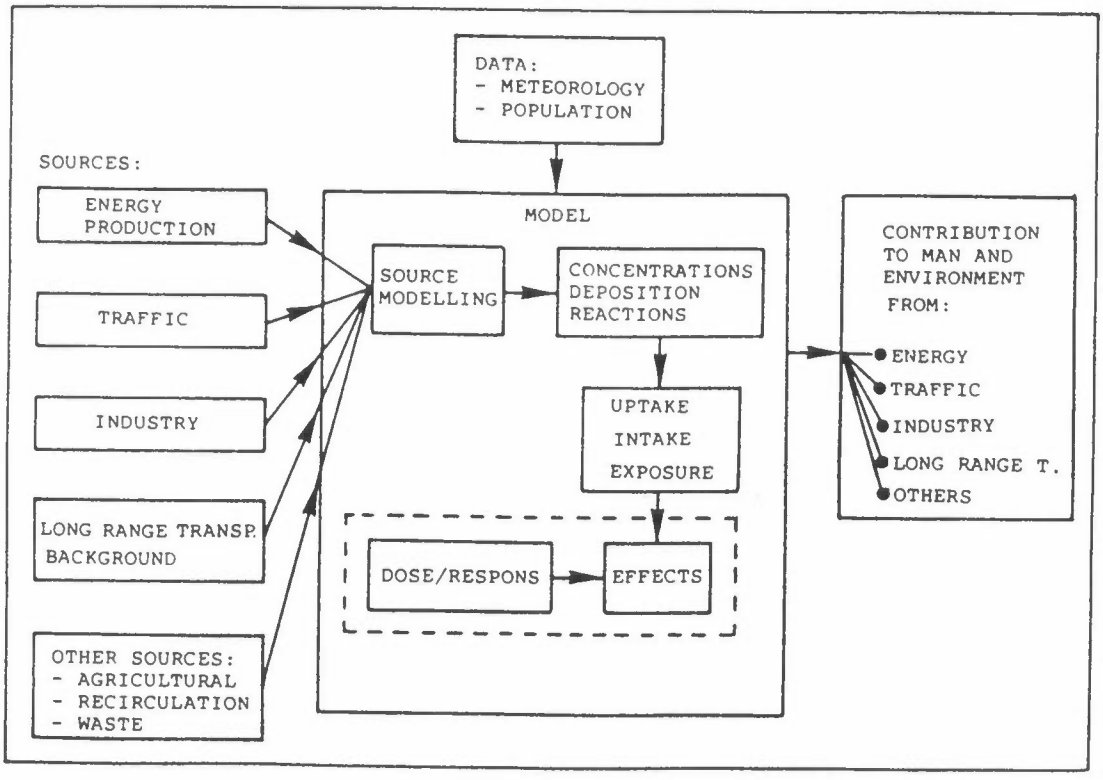


Figure 3: Air pollution model input/output.

A large number of source oriented models are available on all scales in space and time. Considering the different scales of meteorological phenomena as shown in Figure 4, dispersion models will have to focus on different parameters on the different scales.

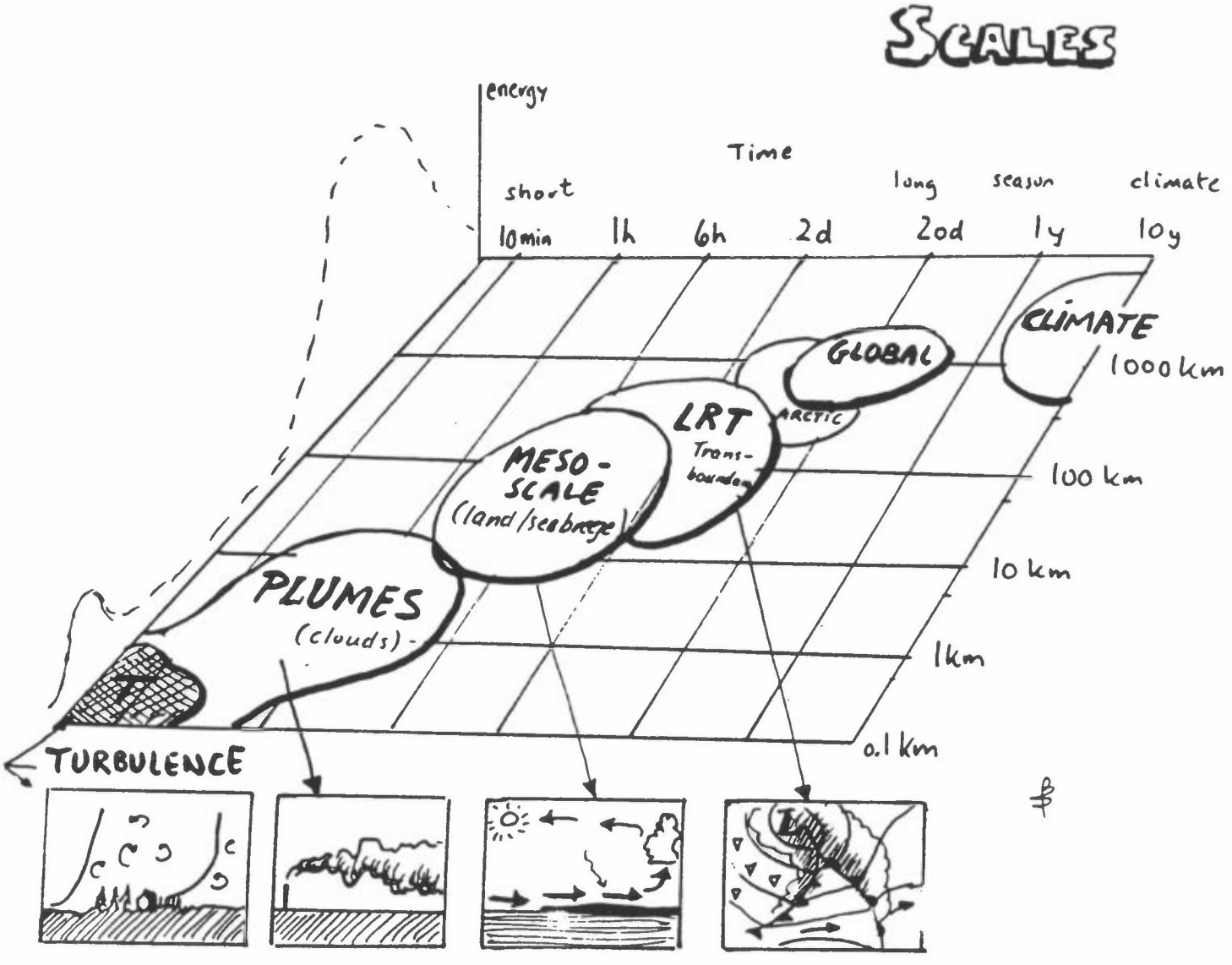


Figure 4: Space and time scales of meteorology.

On the larger scale transport phenomena, chemical transformation and deposition will play an important role, while on the local scale turbulence, buoyanzy effects and surface roughness changes will be more important.

Early air quality model development was based on local scale problems. During the 1970s long range air pollution transport models have been developed. Mesoscale models covering distances of 10 to 300 km have been scarce. Investigations of mesoscale circulations such as land/sea breeze systems have been some of the limitations in obtaining input to mesoscale models. These models therefore often include advanced three-dimensional meteorological models for generating the input to the dispersion models. In the following we will concentrate on local air pollution models.

2 DISPERSION MODELS FOR LOCAL SCALE AIR POLLUTION

A large number of different mathematic models for dispersion calculations exist and is in practical use throughout the world. The different models treat the various elements of modeling such as; source characteristics transport, diffusion, bouyancy, deposition, chemical reactions etc., differently. The selection of what kind of dispersion model to use is largely dependent upon the problem specification (Figure 5).

The different models may roughly be devided into four categories corresponding to the solution methods that are applied:

- Gaussian type models
- Numerical models (from eq. of continuity)
- Puff trajectory type models
- Box models
- Statistical models.

Gaussian type models are based on Gaussian (normal) probability distribution of the concentration (particle density) in both vertical and horizontal crosswind directions about the plume centerline. These models represent a simple analytical solution of the continuity equation which require homogeneous and steady state conditions. We will discuss these type of models in details later.

Numerical models are based upon numerical solution of the continuity equation, which we will discuss later. Several numerical schemes for solving the equation, varying in complexity, accuracy and computing speed have been applied. The solution will depend upon the scale of the problem (see Figure 4).

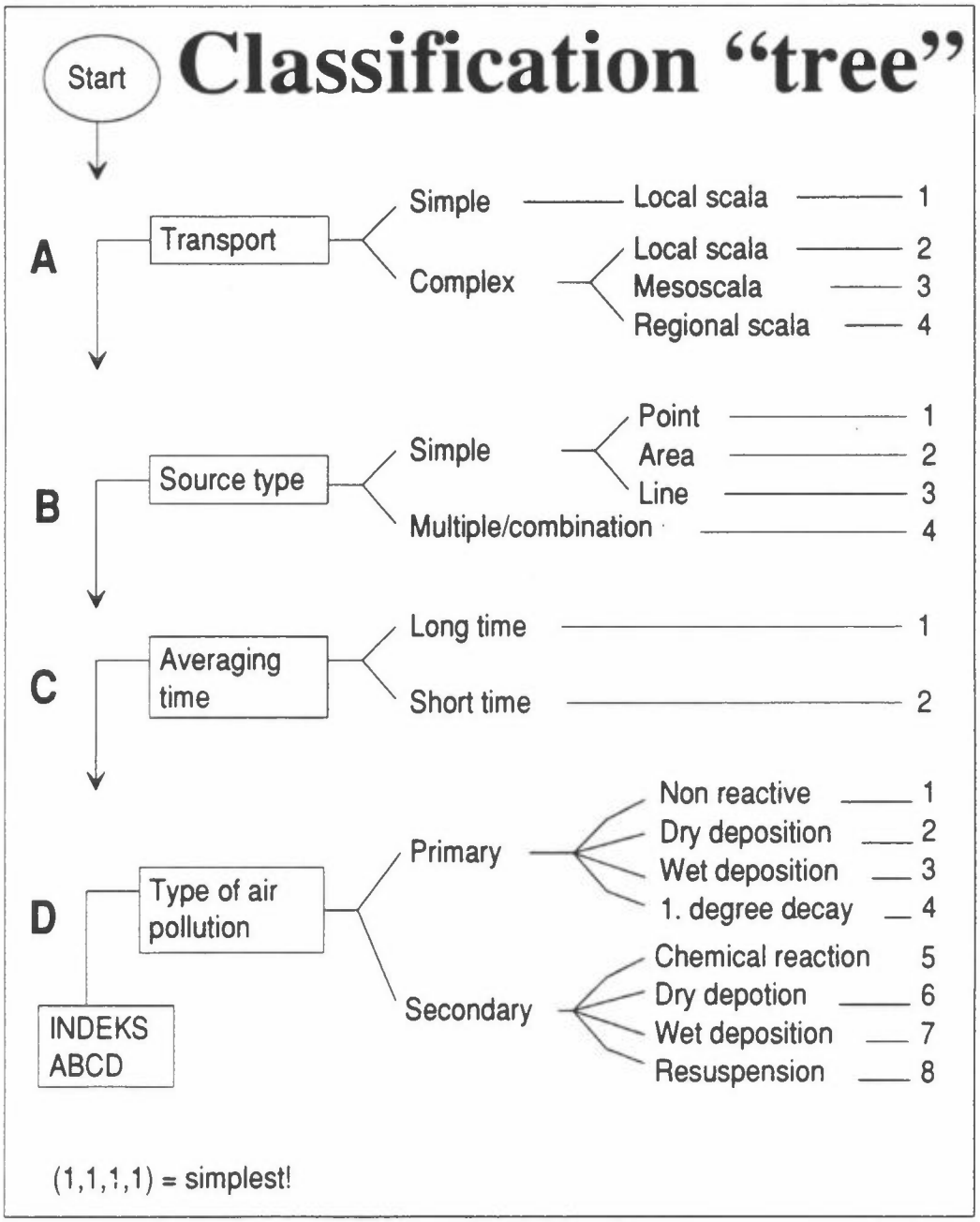


Figure 5: Classification of dispersion models.
The resulting index ABCD give:
A: Complexity in meteorolgy
B: Type of source of major concern
C: Desired averaging time
D: Type and characteristics of pollutant.
The system gives a total of 256 problem classifications and the resulting index can be used in the seach for approach and backgroundmaterial.

The numerical transport/diffusion models overcome the difficulty of Gaussian plume models to simulate complicated situations like instationary and inhomogeneous conditions as well as calms and weak wind situations.

These complicated situations require a detailed knowledge of the three-dimensional field structure and its temporal variation for the relevant meteorological variables and, sometimes, of the initial three-dimensional concentration field as an initial condition for the numerical solution of the working equation. Thus, either a large amount of input data, additional restrictive assumptions, or a comprehensive closed set of coupled differential equation for all relevant variables is necessary for an adequate treatment of the problem.

Puff trajectory type models are estimating the spread of air pollution along the trajectory of a simulated puff release. It is necessary to know the wind field of the area. The dispersion of each individual puff can be handled in many different ways. Often simple gaussian concentration distributions are assumed along the horizontal and vertical axis. Concentrations of specific receptors over a specified averaging times are estimated by the sum of a complex sequence puffs. These models are often applied in complex meteorological situations with time varying winds (land/sea breeze, mountain/valley wind etc.).

Box-models are based on the idea, that the temporal variation of air pollution concentration in a clearly defined area can be described by the consideration of input and output, of sources and sinks within a schematic "budget-box".

It has to be distinguished between simple box-models, which consider whole urban areas as a single box, and, thus only allow for spatially undifferentiated predictions of short- or long-range trends of urban air pollution concentration, and multiple box-models in which the urban area is divided into a grid of horizontal boxes, thus, permitting spatial differentiation.

There exist several transitional concepts between box-models and finite difference treatments of the full partial differential equation for atmospheric diffusion on the one hand, and between box-models and Gaussian models on the other hand.

Statistical models try to associate the probabillity distribution of pollutant concentration fields to a set of meteorological parameters that characterizes the actual meteorological situation. These models comonly make use of multiple regression analyses of measured data. The results are described by means of empirical relations, tabulation schemes, empirical orthogonal functions, or variational methods. Statistical models can usually not be applied in planning or for environmental, impact analyses for planned emission sources. They have, however, been used for short term air quality forecasts, based upon the weather forecast available.

3 THE BASIC EQUATION OF CONTINUITY

Transport- and dispersion models are based on numerical solutions of the continuity equation, for instance on the form:

$$\underset{}{\frac{\delta C}{\delta t}} = \underset{1}{-\nabla_h (\vec{v}_h C)} \underset{2}{- \frac{\delta}{\delta z} (wC)} \underset{3}{+ \nabla_h (K_h \nabla_h C)} \underset{4}{+ \frac{\delta}{\delta z} (K_z \frac{\delta C}{\delta z})} \underset{5}{+ Q} \underset{6}{+ S}$$

where $\nabla_h = \vec{i}\delta/\delta x + \vec{j}\delta/\delta y$.

The change of concentration in time ($\delta C/\delta t$) is dependent upon five basic processes:

1. horizontal advection
2. vertical transport
3. turbulent diffusion horizontally (K_h)
4. turbulent diffusion vertically (K_z)
5. sources, Q
6. sinks (deposition, decay etc.), S

Several numerical scheemes have been applied for solving the continuity equation, as mentioned above (numerical models). We

will in the following look at some analytical solutions used in local air pollution dispersion problems.

4 THE GAUSSIAN SOLUTION

4.1 PUFF RELEASE

During very simplified meteorological conditions we might assume:

- no wind ($v_h = w = 0$)
- homogeneous, stationary turbulence (K = const.)
- no deposition or reactions (S = 0).

For an instantaneous point source (puff) the equation simplifies to read:

$$\frac{\delta C}{\delta t} = K_x \frac{\delta^2 C}{\delta x^2} + K_y \frac{\delta^2 C}{\delta y^2} + K_z \frac{\delta^2 C}{\delta z^2}$$

where $\int\int\int C dx dy dz = Q_{i\,p}$

An analytical solution for the concentration C can be written:

$$C = Q \cdot \exp(TURB)/(4\pi t)^{3/2}\ [(K_x K_y K_z)]$$

where $TURB = -(x^2/K_x + y^2/K_y + z^2/K_z)/4\ t$

If we further assume that the concentration distribution horizontally (y) and vertically (z) perpendicular to the wind direction (x) is normally distributed (Gaussian) we have obtained the Gaussian model for a puff release with $\sigma = (2\ Kt)^{1/2}$.

4.2 CONTINUOUS SOURCE

If we further assume a continuous release of gas from a speci-

fic point source with release rate Q we can obtain a solution well known as the Gaussian plume model.

For meteorological conditions assume:

- Fickian diffusion (K = const.)
- constant wind (u) along x-axis
- $x = u \cdot t$
- no deposition or reactions
- $\sigma = (2Kt)^{1/2}$
- total plume reflection from the surface

One solution of the Gaussian plume might be written:

$$C = Q \cdot EY \cdot EZ/(\pi \cdot \sigma_y \cdot \sigma_z \cdot u)$$

where $EY = \exp(-y^2/2\sigma_y^2)$

$EZ = \exp(-h^2/2\sigma_z^2)$

4.3 THE GAUSSIAN PLUME MODEL

Gaussian type dispersion models are the most commonly applied models in practical use to day. The equation for calculating the concentration (C) at groundlevel assuming total reflection of the plume at the surface can be written:

$$C = Q\,[\exp(-H^2/2\sigma_z^2) \cdot \exp(-y^2/2\sigma_y^2)]/(\pi\sigma_y\sigma_z \cdot u)$$

where Q = release rate (μg/s)

H = effective plume height (h_s +dh)

σ_y, σ_z = dispersion parameters (m)

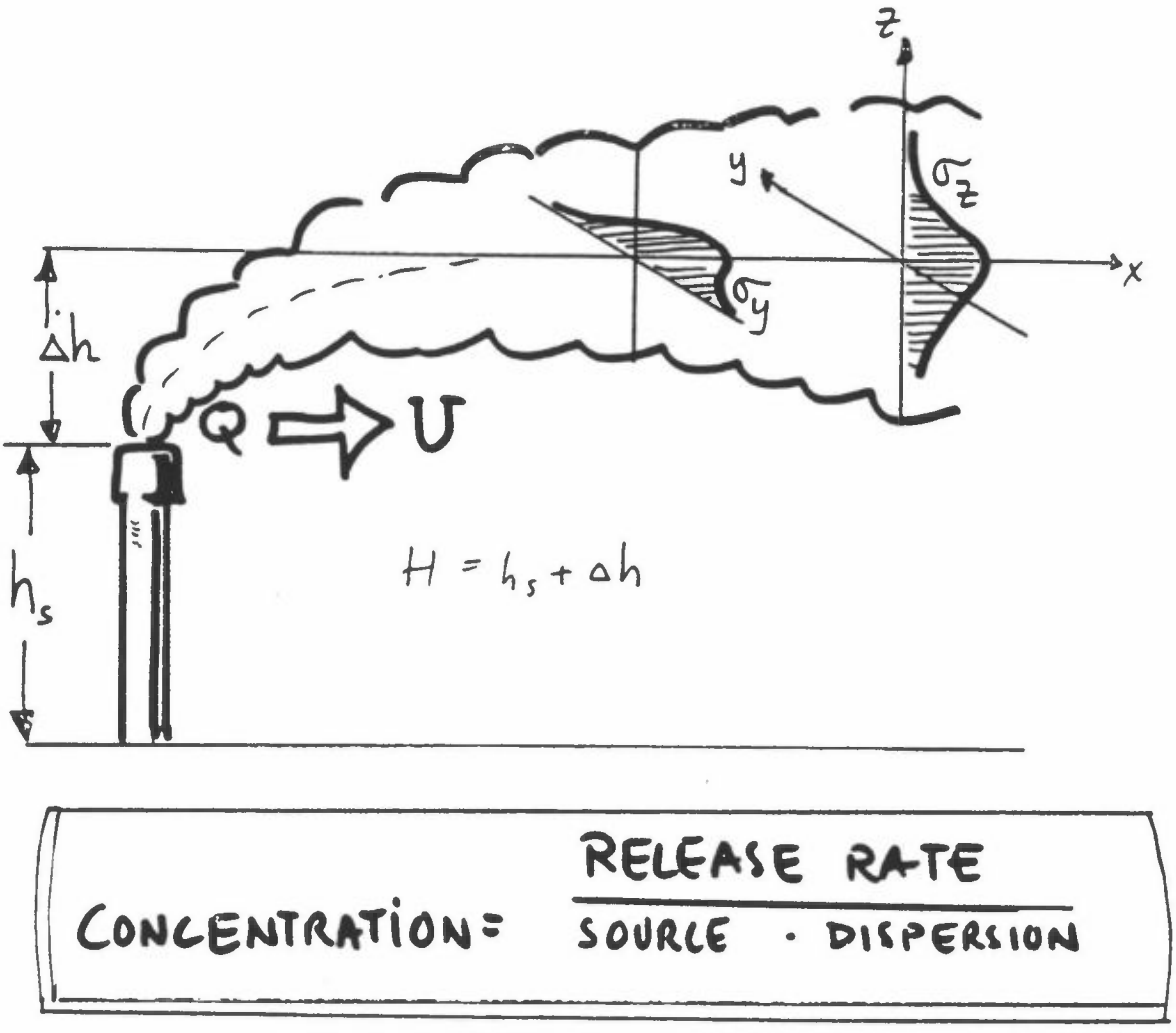


Figure 6: The consept of the Gaussian plume model.

The co-ordinate y refers to horizontal direction at right angles to the plume axis, and z is the height above the ground which is assumed to be flat and uniform.

The parameters σ_y and σ_z are the standard deviations of the concentration distribution in y and z directions respectively. These parameters are usually referred to as the diffusion parameters. The values of σ_y and σ_z are dependent upon the turbulent state of the atmosphere, which again is dependent upon mechanical induced turbulence (wind shear, wind profile) and convective turbulence (temperature profile).

4.3.1 Stability classes

For estimate of σ_y and σ_z in the absence of proper turbulence measurements the turbulent state and the stability of the boundary layer is usually devided into classes, preferably by a simple scheme based on inexpensive measurement data. The most widely used scheme was developed by Pasquill and was modified slightly by Turner in 1961. By this classification the following classes were identified:

A = extremely unstable (low wind, summer, day time)
B = moderately unstable
C = slightly unstable
D = neutral (overcast high winds)
E = slightly stable
F = stable (inversions, cold winter nights)

A simplified classification scheme can be used based upon temperature gradient measurements along a meteorological tower. As input to long term average concentration estimates (CDM models) the follwing classification can be used:

Class	Temp. gradient dT (deg/100 m)	Correspond to: Pasquill	Klug	Brookhaven
Unstable	$dT < 1$	A + B + C	IV + V	$B_1 + B_2$
Neutral	$-1 \leq dT < 0$	D	$III_1 + III_2$	C
Sligtly stable	$0 \leq dT < 0$	E	II	-
Stable	$dT \geq 1$	F	I	D

4.3.2 Diffusion parameters

The diffusion parameter σ_y and σ_z can be taken from empirical curves as a function of the distance from the source (Figure 7).

Such curves have been established by several authors based upon

various types of dispersion experiments. To day estimates are usually performed by computers or caluclators and most people would rather have a formula than a graph.

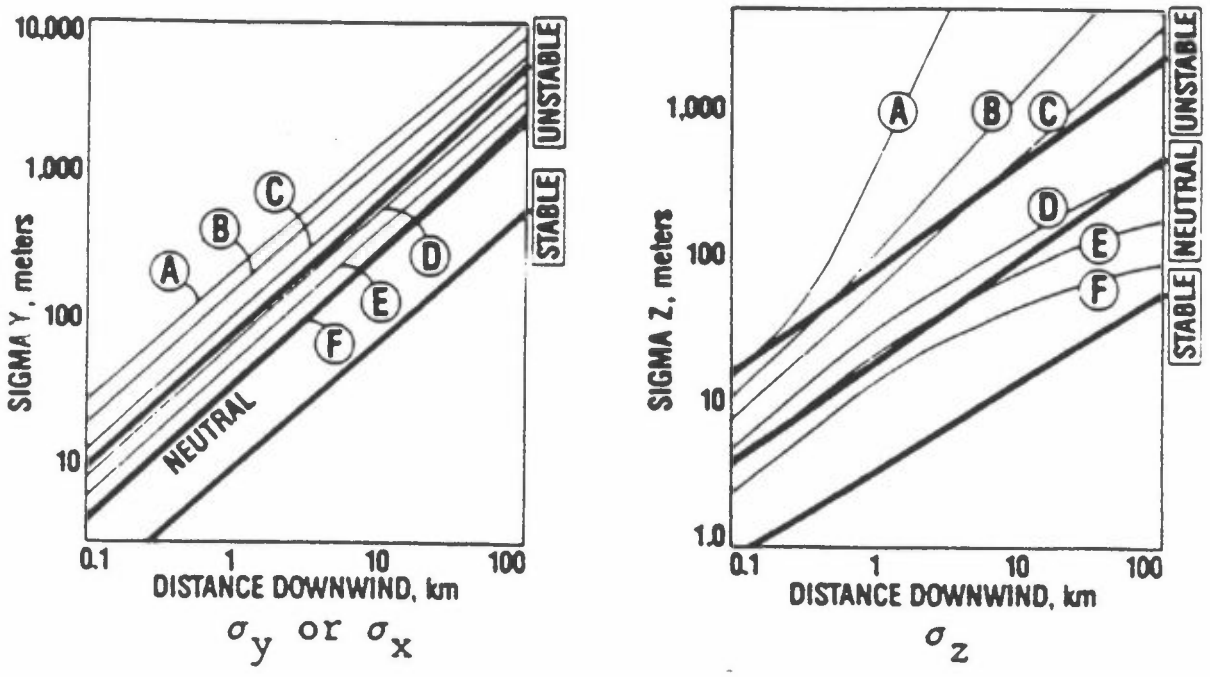


Figure 7: Dispersion coefficient σ_y and σ_z as functions of down wind distance from the source (empirical values based upon dispersion experiments).

The most widely used formula has been established as the power law of distance:

$$\sigma_y = ax^p \quad \text{and} \quad \sigma_z = bx^q$$

Numerical values for a, p, b and q have been established for different surface conditions, for low and high stacks and for area sources as shown in Table 2.

Table 2: Parameter values for diffusion coefficients $\sigma_y = ax^p$, $\sigma_z = bx^q$.

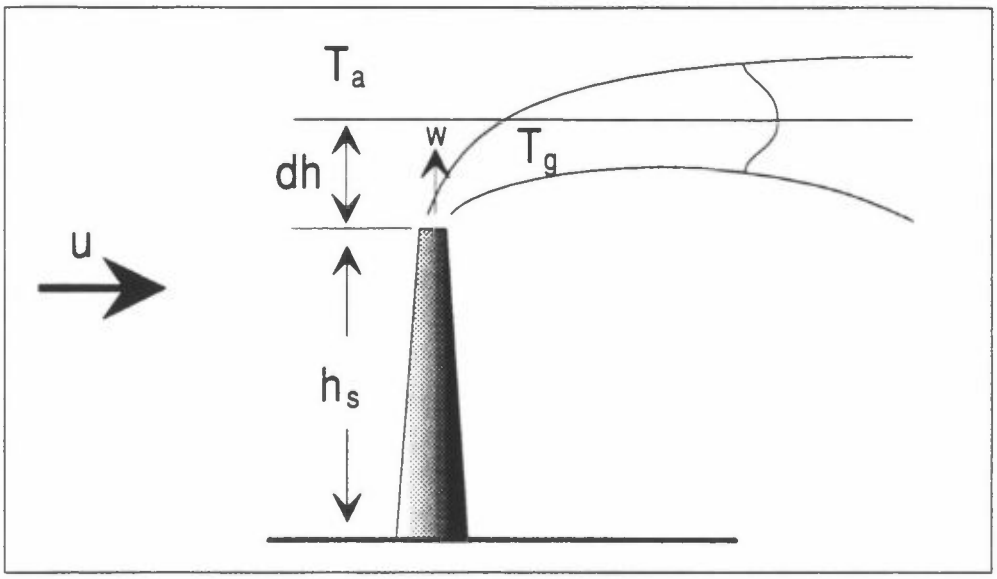
Source and surface specifications	Coefficients	Unst.	Neutr.	Sl.stable	Stable
Surface	a	0.31	0.22	0.24	0.27
Emission	p	0.89	0.80	0.69	0.59
Low stacks	b	0.07	0.10	0.22	0.26
Smooth surface	q	1.02	0.80	0.61	0.50
Surface and low					
sources (area	a	1.7	0.91	1.02	-
sources)	p	0.72	0.73	0.65	-
Rough surface,	b	0.08	0.91	1.93	-
urban	q	1.2	0.70	0.47	-
High stacks	a	0.36	0.32	0.31	0.31
Smooth to	p	0.86	0.78	0.74	0.71
medium rough	b	0.33	0.22	0.16	0.06
surface	q	0.86	0.78	0.74	0.71
High stacks	a	0.23	0.22	1.69	5.38
Rough surface	p	0.97	0.91	0.62	0.57
	b	0.16	0.40	0.16	0.40
	q	1.02	0.76	0.81	0.62

We will return to other ways of describing the turbulent diffusion (spread) of gas plumes in the next chapter.

4.3.3 The effective plume height, H

The effective plume height (H) is defined as the total plume height above the ground, which is the sum of the stack height (h_s) and plume rise (dh).

Plume rise estimates are very important when determining maximum ground level concentrations due to emissions from stacks. Maximum ground level concentrations is roughly proportional to the inverse square of the effective stack height. Plume rise (which in some cases might increase the plume height compared to the stack height with a factor 2-10), can thus reduse the ground level concentration by a factor 100.



Plume Rise

$$dh = 1{,}6 \cdot F^{1/3} \cdot (10 \cdot h_s)^{2/3}/u_s$$

$$F = 9{,}81 \cdot w \cdot (d/2)^2 \cdot (T_g - T_a)/T_a$$

w	=	exitgas velocity (m/s)
d	=	stack diameter (m)
T_g	=	plume gas temperature
T_a	=	ambient air temperature
u_s	=	wind speed at stack level

Figure 8: Plume rise (bent over plume).

The plume rise is a combination of buoyancy flux

$$F = g \cdot V (T_g - T_a)/T_g$$

and momentum flux

$$M = w \cdot V$$

where: V = volume flux = $w \cdot r^2$
T_g = plume temperature
T_a = ambient air temperature
w = vertical plume speed

Assuming that F_0 is the buoyancy flux at the stack exit, Briggs recommended for buoyancy dominated plumes (power plants etc...) that

$$dh = 1.6 \cdot F_0^{1/3} x^{2/3} u^{-1}$$

This famous "2/3 law" has shown to agree well with observations.

During stable atmospheric conditions the plume vertical motion is slowed down giving a plume rise which is inverse proportional with the stability

$$s = g(\delta T_a/\delta_z + 0.01)/T_a$$

The plume rise in these conditions can be written:

$$dh = 2.6 (F_0/(u \cdot s))^{1/3}$$

4.3.4 Wind speed

The wind speed u that enters into the Gaussian plume model can not go to zero. Anemometers measuring wind near the surface may register u = 0 (calm conditions). However, in the planetary

boundary layer where plumes are moving the air movements very seldom stop entirely. At "calm conditions" the windspeed u is usually for modelling purposes set: u = 0.5 m/s.

For estimating plume rise the wind speed should be representative of that at the stack height. We thus need a method for estimating wind speed at a given height z.

In Gaussian plume models a simple power law formula has been applied:

$$u = u_{10} \ (z/10)^m$$

where u_{10} is the observed wind at 10 m. The power of m can be given as a function of stability and surface conditions.

Table 3: The values of m in the power law wind profile.

Surface	Unstable	Neutral	Light stable	Stable
Urban Rural	0.2 0.1	0.25 0.15	0.4 0.35	0.6 0.5
"Kilder"	0.2	0.28	0.36	0.42

5 ATMOSPERIC DISPERSION MODELING BASED UPON BOUNDARY LAYER PARAMETERIZATION*

Characteristic scaling parameters in the planetary boundary layer (PBL), as presented by Sivertsen et al. (1985)* have been applied to estimate the dispersion of nonbuoyant gaseous pollutants. Where only standard surface data are available, methods are suggested for estimation of wind and temperature profiles.

Vertical and lateral spread is treated separately, and the choice of parameters for the dispersion models depends upon the actual state of the atmospheric boundary layer. The concentration distribution in teh lateral direction is usually taken to be Gaussian, while for the vertical, serveral different approaches are suggested.

To illustrate the application of the boundary layer scaling parameters used in dispersion estimates, results from several dispersion experiments under different atmospheric conditions have been used.

The states of the PBL

In the different idealized states of PBL, different scaling parameters describe the dispersion of passive gaseous air

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* From a paper by:
B. Sivertsen[1], S.E. Gryning[2], A.A.M. Holtslag[3], J.S. Irwin[4]. (NIU FF 29/85)
1 Norwegian Institute for Air Research
P.O. Box 64, 2001 Lillestrøm, Norway
2 Risø National Laboratory, Roskilde, Denmark
3 Royal Netherlands Meteorological Institute,
The Bilt, The Netherlands
4 Meteology and Assessment Division, Environmental Sciences
Research Laboratory, E.P.A. Research Triangle Park, USA
Atmos. Env., Vol 21, pp. 79-89, 1987.

pollutants. Dispersion in the PBL is given by three length scales:

z = height above the surface
h = mixing height
L = Monin-Obukhov length (see Figure 9)

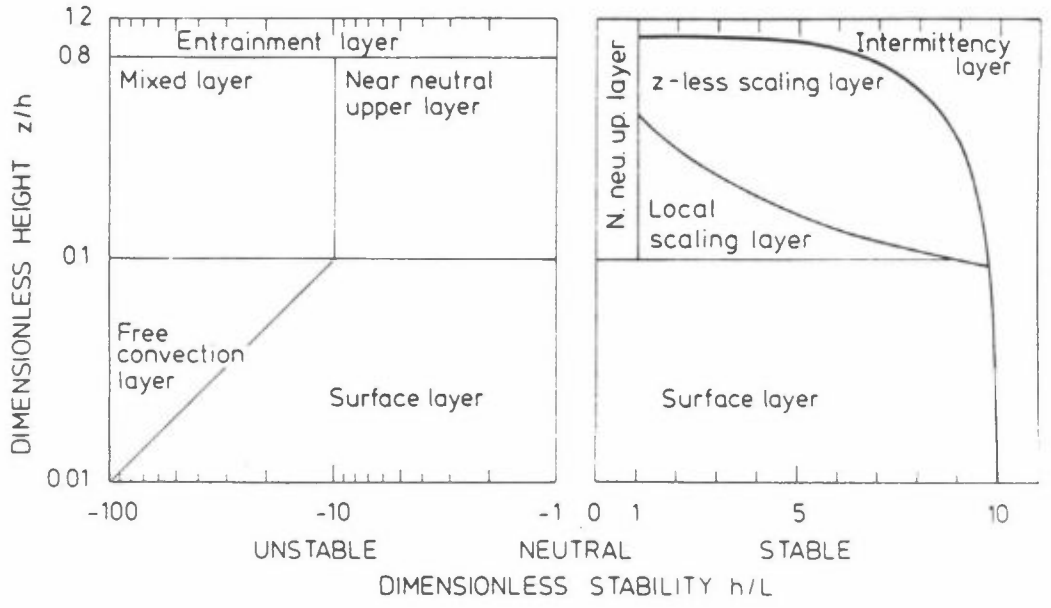


Figure 9: The scaling regions of the atmospheric boundary layer, shown as function of the dimensionless height z/h, and the stability parameter h/L. When used to determine dispersion regions, the dimensionless height is replaced by h_s/h, where h_s is the source height.

It is possible to establish two independent dimensionless parameters:

z/h is a relative height, and
h/L is a stability parameter for the whole mixing layer depth (h).

Figure 9 summarizes schematically the limits of validity of the different scaling techniques distinguishing between regions commonly mentioned in the literature.

To obtain the Monin-Obukhov length, L, it is necessary to estimate the friction velocity, u_*, which is a function of the surface roughness, z_0.

In this paper, L is estimated from measurements of windspeed at one level and the temperature difference between two levels. From Monin-Obukhov theory for the atmospheric surface layer:

$$L = u_* T/(k\ g\ \theta_*)$$

where θ_* is the surface layer scaling temperature, T is the ambient air temperature, k is th von Karman constant ~0.4 and g the acceleration of gravity.

Applying this so-called profile method, the vertical profiles of wind speed (u(z), and potential temperature, $\theta(z)$, can be expressed as functions of u_*, θ_*, z_0 and L in the surface layer.

At low winds and stable conditions, L is often less than 10 m. The surface layer is thus very shallow, and pollutants are often released above the surface layer. Above this thin, stable surface layer the turbulent mixing of pollutants is not so well described and documented as in the surface layer. Using a local Obukhov length, Λ, the turbulence is no longer described by z (z-less layer). For still larger stabilities, the present similarity theories break down, and the transport and

dispersion of pollutants has to be described by other processes, usually difficult to characterize.

Dispersion estimates

LATERAL dispersion

Most dispersion experiments showed that the lateral distribution of the plume usually resembles a Gaussian distribution (e.g., Sivertsen, 1978) Even under very stable conditions, with releases of tracers in and above the surface layer, the lateral concentration distribution near the surface is close to Gaussian.

Pasquill derived from Taylor's statistical theory for plume dispersion the following expression, from estimating the standard deviation of the lateral crosswind concentration distribution.

$$\sigma_y = \sigma_v \; t \; f_y \; (t, T_y)$$

where f_y is a universal function of transport time, t, and a time scale, T_y, for the dispersion process. This scheme is found to perform best when:

$$f_y = (1 + 0.9 \; (t/T_y)^{0.5})^{-1}$$

The eq. above is also in agreement with other findings. (Sivertsen (1978)). For practical use it is suggested that T_y ~1000 s for elevated sources, and T_y ~300 s for ground-level sources. The standard deviation of wind fluctuation, σ_v, (or wind direction fluctuation σ_θ) should be measured directly. For the tracer experiments described here, σ_v and σ_θ

were measured over an averaging time, corresponding to the measured concentrations. If the wind fluctuations are not measured directly, σ_v can be estimated from u_*, L and h:

$$(\sigma_v/u_*)^2 = 0.7(-h/L)^{2/3} + 2.7(1-z/h)^2/(1+2.8z/h)^{2/3}$$

In the following, methods are given for estimating crosswind integrated concentrations $C_y(x)$, at a distance, x, for the different regimes presented in Figure 6. When these values of C_y are estimated from the various scaling parameters, the concentration at a given point downwind, C(x,y), can be calculated from:

$$C(x,y) = C_y \exp(-y^2/2\sigma_y^2)/(\sigma_y (2\pi)^{1/2})$$

This method is capable of treating non-Gaussian vertical concentrations distributions.

STABLE CONDITIONS

Turbulent dispersion in the stable boundary layer is not as well understood as in the unstable boundary layer. This is especially the case for elevated sources, when the wind weakens to less than ~1 m/s during surface inversions. Since the similarity profiles are only valid for $z_0 << z < L$, and L often is less than ~10 m, the profile method, mentioned above, should only be applied to a shallow layer of the atmosphere. The temperature difference should be measured directly.

At the bottom is a mixed layer of thickness h, there is some controversy as to whether simple equations for h as a function of friction velocity $u_*(z_0)$, and stability L, can be applied. The most common formula for h is:

$$h = a(u_* L/f)^{0.5}$$

where f is the Coriolis parameter, and a = 0.4. Reasonable

agreement has been found between estimates obtained with Eq. (6) and observations in level terrain.

The stable surface layer. In the stable surface layer, where $(z/h) \leq 0.1$, the Monin-Obukhov theory applies. Most turbulent quantities are described by z/L. The vertical eddy diffusivity for matter is described by:

$$K = k\, u_* \, z/\Phi_h\,(z/L)$$

where Φ_h is an empirical function of stability z/L.

Assuming that the vertical profiles of K(z) and the wind speed u(z) can be represented by power laws, a general solution of the two-dimensional dispersion equation can be written:

$$C_y\,(z)/Q = (A/\bar{z}\bar{u})\, \exp\,[-(Bz/\bar{z})^s\,]$$

where A and B are functions of the shape parameter s. The mean height of the gas cloud, $\bar{z}$, and the mean wind speed, $\bar{u}$, transporting the cloud is determined iteratively as a function of the downwind distance x.

Local and z-less scaling region. Above the thin stable surface layer, the turbulent mixing of pollutants is not as well described and documented as in the surface layer. Experiments show that local z-less scaling arguments can be employed to describe the dispersion process.

The local Obukhov length Λ can then be written as:

$$\Lambda = \tau^{3/2} / (k \overline{w\theta} (g/T))$$

where τ is the kinematic stress.

For applications of local and z-less scaling in dispersion estimates, vertical profiles of τ and $\overline{w\theta}$ are needed. These can be obtained by modelling the evolution of the stable boundary layer, and using a closure hypothesis of a critical Richardson number, Ri = 0.2. This lead to a simpel expression for Λ/L:

$$\Lambda/L = (1-z/h)^{5/4}$$

with h as given in Eq. 6.

To characterize the dispersion in these regions, the use of a Gaussian-type plume model is recommended. Direct measurements of σ_v and σ_w are preferred and strongly recommended in these layers. The averaging times should correspond to the averaging times associated to the concentration estimates. These values can also be applied in expressions such as Eq. 2 and 3 for the vertical spread. The dispersion time scale for vertical diffusion, T_L, is of the order of 50 s. The vertical dispersion for "elevated releases" can be expressed as:

$$\sigma_z = \sigma_w \, t(1 + t/2T_L)^{-0.5}$$

where T_L was approximately 8 to 12 s. In stable layer experiments performed at NILU we found a better fit to data using Eq. 3, with T_L = 50 s. If σ_w is not measured directly, we suggest the use:

$$\sigma_w = 1.3 \, u_* \, (1-z/h)^{3/4}$$

where 1.3 u_* is the value of σ_w in the surface layer.

UNSTABLE CONDITIONS

The characterization of turbulence within the unstable boundary layer is better understood and documented than in the stable counterpart. The important scaling parameters for description of turbulent diffusion are different in the different scaling regions.

In the follwing we will examine data from dispersion experiments performed by NILU.

The unstable surface layer. In the unstable surface layer, given by $z/h < 1.0$ and $-z/h < 1$, the Monin-Obukhov theory applies, and the dispersion can be described by the same set of equations as given for the stable surface layer. The empirical functions and parameters might be different.

The agreement between observed and estimated concentrations in the unstable surface layer is good, even if there seem to be a slight tendency of underestimating.

The mixed layer. Mixed layer scaling is found appropriate for $0.1 > z/h < 0.8$ and $-h/L \geq 10$. Briggs reanalyzed laboratory simulations reported by Willis and Deardorff and found that the mean crosswind integrated dimensionless concentration could be expressed:

$$C_y h\, U/Q = 0.9\, X^{9/2} \cdot z_s^{-11/2} \left[Z_s^{-3/4} + 0.4 \cdot X^{9/2} \cdot Z_s^{-9/2}\right]^{-4/3} + \left[1 + 3Z_s^{1/2}\, X^{3/2} + 50X^{-9/2}\right]^{-1}$$

where $X = (x/h)w_*/U)$,

z_s is the source height, $Z_s = (z_s/h)$ and $w_* = (g\ h\ w'\theta_o'/T)^{1/3}$ is the conventive velocity scale for the turbulence. The equation applies for nonbuoyant releases when $0.04 \leq Z_s < 1$.

The free convection layer. The free convection layer is apparent above the surface layer, typically for $z > -L$ and below $z \sim 0.1\ h$. The controlling parameters z and the surface heat flux $\overline{w'\theta_o'}$ describe a scaling velocity

$$u_f = (\overline{w'\theta_o'}\ zg/T)^{1/3}$$

The normalized crosswind integrated concentration is given by:

$$C_y\ Uz/Q = b((u_f/U)(x/z))^{-3/2}$$

where $b = 0.9$. The free convection similarity scaling has been found to apply for downwind distances of $0.03 < (u_f/U)(x/z) < 0.23$.

The near neutral upper layer. In the near neutral upper layer, where -L becomes large ($-h/L < 10$) and $0.1 < (z/h) < 0.8$, direct measurements of σ_w and σ_v are recommended. These values can be applied in Gaussian type dispersion models with σ_y and σ_z as given before.

Otherwise σ_w and σ_v could be approximated from profiles of lateral and vertical variances.

$$(\sigma_w/u_*) = 1.54\ \{z/(-kL)\}^{2/3}\ \exp(-2z/h) + 1.457\ (1-z/h)^2$$

The estimates of crosswind integrated concentration, in the near neutral upper layer, are compared with observations from tracer experiments performed at NILU. The Gaussian model, with

$$f_z = (1 + 0.9(t/T_L)^{0.5})^{-1}$$

and T_L = 500 s slightly underestimated the observed concentrations (within ~30%).

Discussion

The diffusion of non buoyant gaseous pollutants has been described by different scaling parameters in the different "regions" of the planetary boundary layer.

The lateral dispersion was usually found to approach a Gaussian distribution. In the vertical, however, the concentration distribution can be far from Gaussian.

For the different scaling regions of the atmosphere, methods with different parameters for estimating the crosswind integrated concentrations, as functions of distance from the source, have been suggested and tested versus results from tracer experiments. The parameters were estimated from meteorologcial measurements directly. In this way the transport and dispersion has been directly related to the turbulent state of the atmosphere.

6 MODELS TO CALCULATE CAR EXHAUST POLLUTION

Several line source dispersion models suitable for calculating air pollution concentrations from exhaust emissions along a road have been developed, mainly in the US. Some of the well known models for highways are HIWAY 2, CALINE 1-4 and GM-LINE. Based on recommendations from the EPA, NILU has chosen to use the HIWAY 2 model. This model, and a modified version of it, in which the initial dispersion due to car turbulence is not a function of car speed, is used for roads through areas with dispersed buildings and vegetation.

For street canyons, the basic model used is the APRAC model, a semi-emipirical model developed at Stanford University. In a

Nordic co-operative study, this model was further developed, based on an extensive Swedish-Norwegian measurement data base. It has been designated "Nordic Curbside Pollution Model", and is used extensively to calculate CO and NO_2-concentrations in street canyons.

In a revised version of the Nordic model, a new dispersion module for street canyons, called OSPM, has been developed by the Danish National Air Quality Laboratory. This theoretically based model agrees well with the APRAC-based model for the conditions for which the APRAC-model was valid. However, it describes more accurately the influence of wind direction, and also of the height of the buildings along the street.

Based on the APRAC/OSPM and HIWAY 2 models, NILU has developed an integrated model for calculation of pollution concentrations along road networks, e.g. that of a city. The model is called ROADAIR. So far, CO and NO_2 concentrations may be calculated. Figure 10 shows a block diagram of the model.

Figure 11 gives an overview of the necessary input data.

Figure 12 gives example of results from the calculations. The model has been developed for use on microcomputers with MS-DOS operative system, and is delivered on discett.

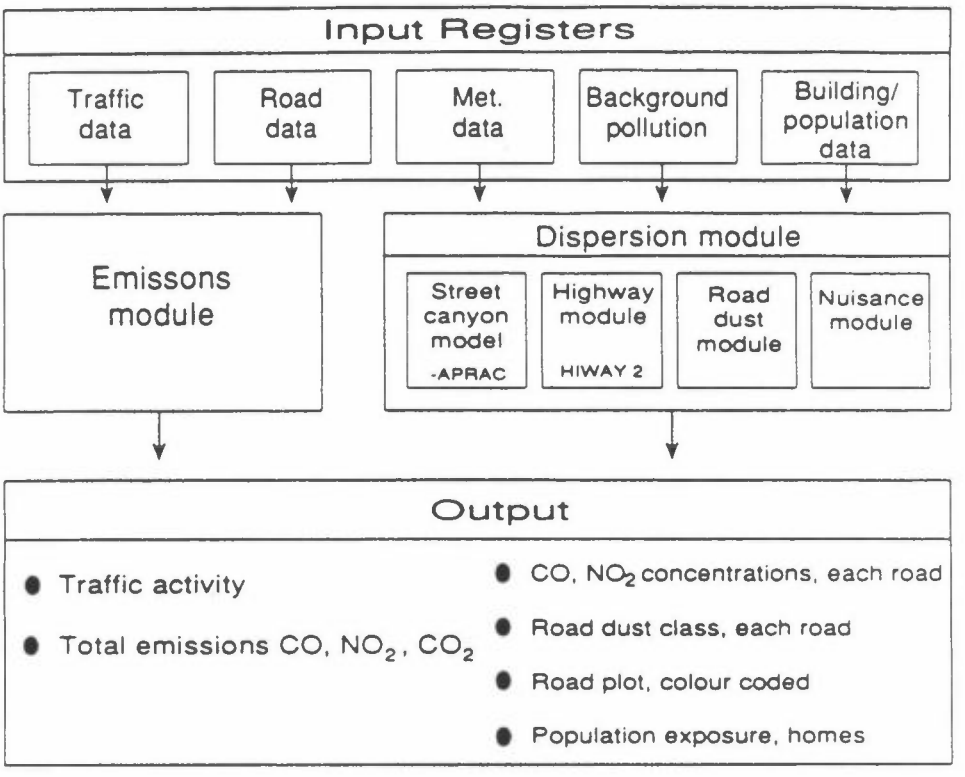


Figure 10: ROADAIR. Simplified block diagram of model

ROAD DATA

(road network separated into straight road segments)

- End point positions
- Road category
- Position in city (centre, outskirts)
- Steepness
- Width
- Building topography (classified)

TRAFFIC DATA

- Annual daily traffic/max. hourly traffic
- Traffic velocity, average/during rush hour
- Heavy duty diesel traffic

BUILDING DATA

- Distance building-road
- No. of apartments/resident units

Figure 11: ROADAIR. Overview of necessary input data.

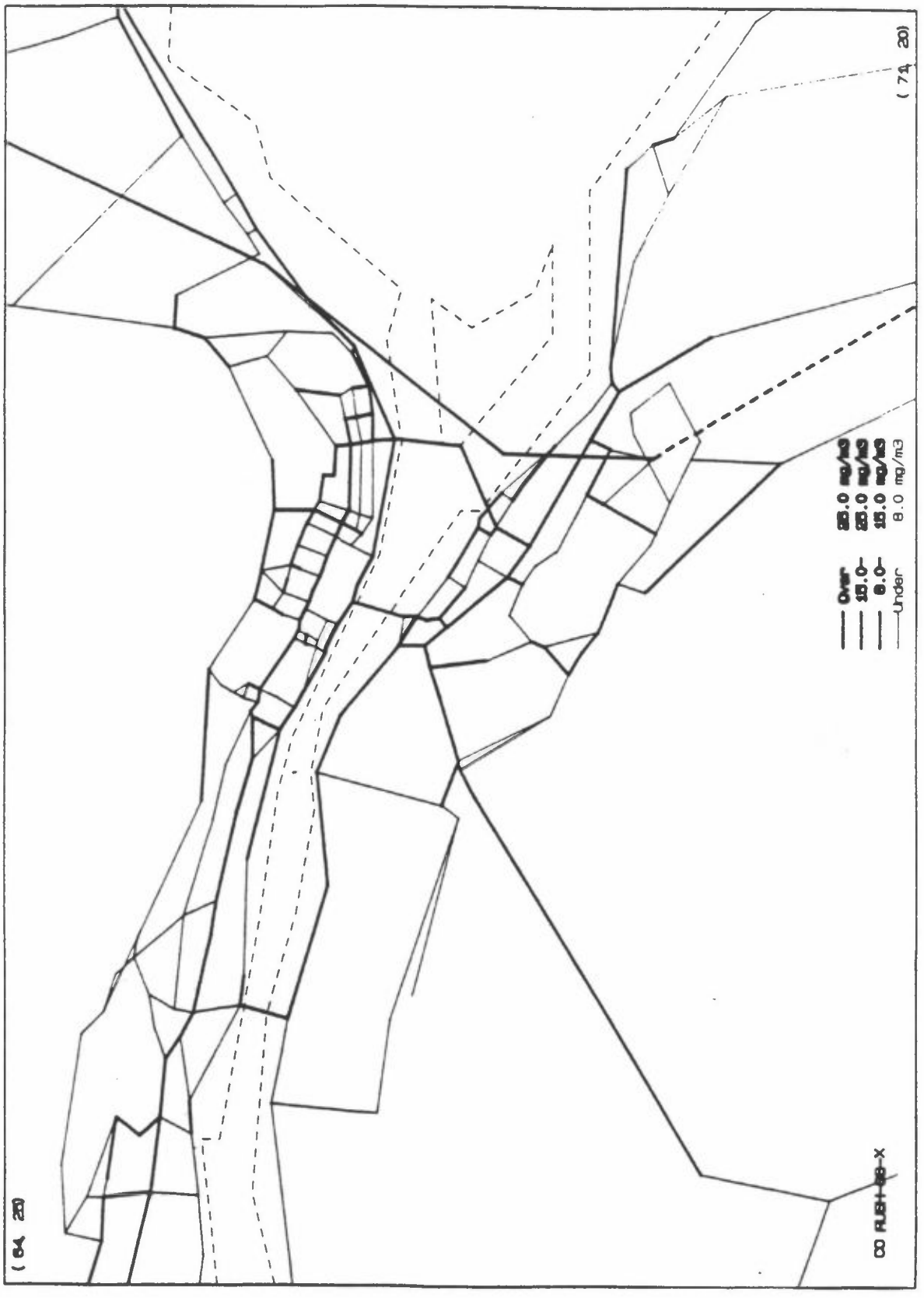


Figure 12: ROADAIR. Example of plot of road system with each road classified according to the calculated maximum 1-hourly CO concentrations. The example shows CO along the road system in the city of Drammen, for 1989.

Figure 13 shows the relative reduction of the maximum 1 hour concentration with distance from the road, as calculated by the HIWAY module in ROADAIR. The figure also shows examples of measured reduction with distance. The examples show long-term concentrations of black smoke particles and deposition of road dust (pr. m^2).

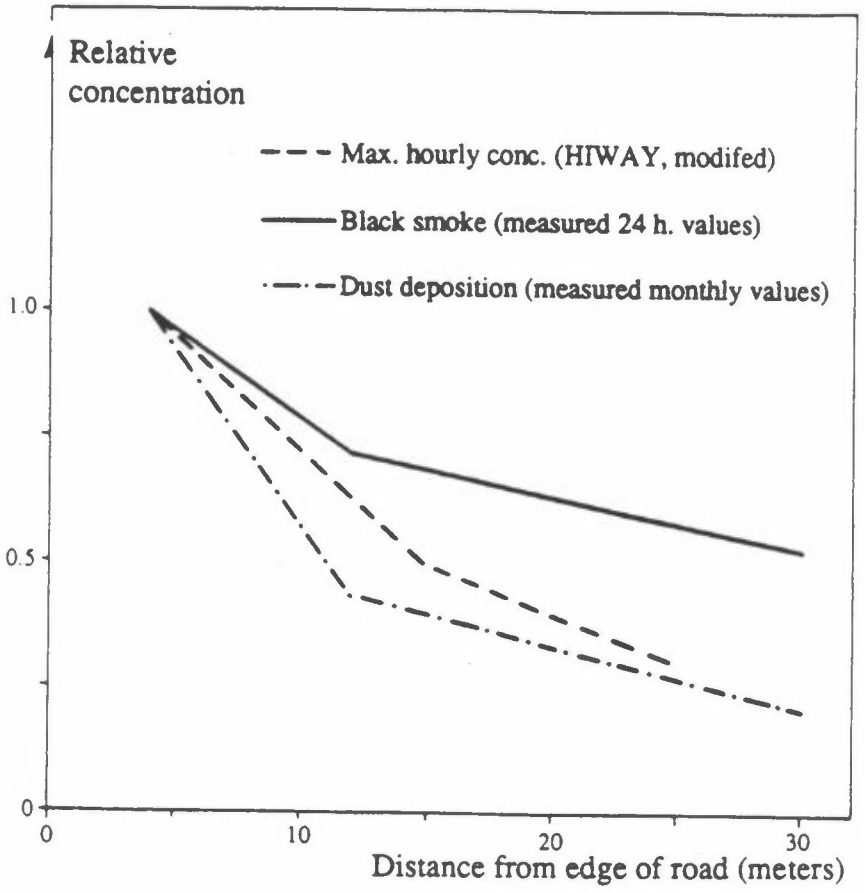


Figure 13: Examples of reduction in air pollution concentrations with distance from a highway.

7 DEPOSITION ESTIMATES

For estimates of deposition of gases, aerosols and particles to the surface, it is necessary to know the terminal falling velocity for large particles, and the deposition velocity for small particles (usually in than 10 micrometers) and gases.

In the two-dimensional version of a simplified continuity equation the concentration charge as a function of distance from the source ($\delta C/\delta x$) can be expressed:

$$u(\delta C/\delta x) = \frac{\delta}{\delta x}\left(K_z \frac{\delta C}{\delta_z} + v_s\ C\right)$$

The deposition rate at the surface $D(g/m^2)$ can be expressed as:

$$D = \left[K_z \frac{\delta C}{\delta z} + v_s\ C\right]_{z \to o} = v_d \cdot C\ (x,o)$$

where the deposition velocity (v_d) is defined as the ratio of deposition rate and surface concentration. The deposition velocity for aerosols is:

$$v_d = v_s + f(K_z)$$

for gases $v_d = [r_a(z) + r_b + r_c]^{-1}$

where : r_a = aerodynamic resistance (turbulence)

r_b = sublayer resistance (plants)

r_c = canopy resistance

Predicted deposition velocities at 1 m for $u_* = 0.5$ m/s is shown for different particle sizes in Figure 14.

For Gaussian models several approximation schemes have been proposed for estimates of deposition. The source depletion method has been most widely applied approach.

$$D = v_d\ C$$

where $C = Q' \cdot E_y \cdot E_z / (2\pi\sigma_y \sigma_z \cdot u)$

Q' expresses the change in source strength due to deposited material as a function of distance from the original source strengt Q_o.

$$Q'(x) = Q_o\ [\exp \int_o^x (dz/SIGZ)^V$$

where: $SIG_Z = \sigma_z \cdot \exp(h^2/2\sigma_z^2)$

$V = -(2/\pi)^{1/2}(v_d/u)$

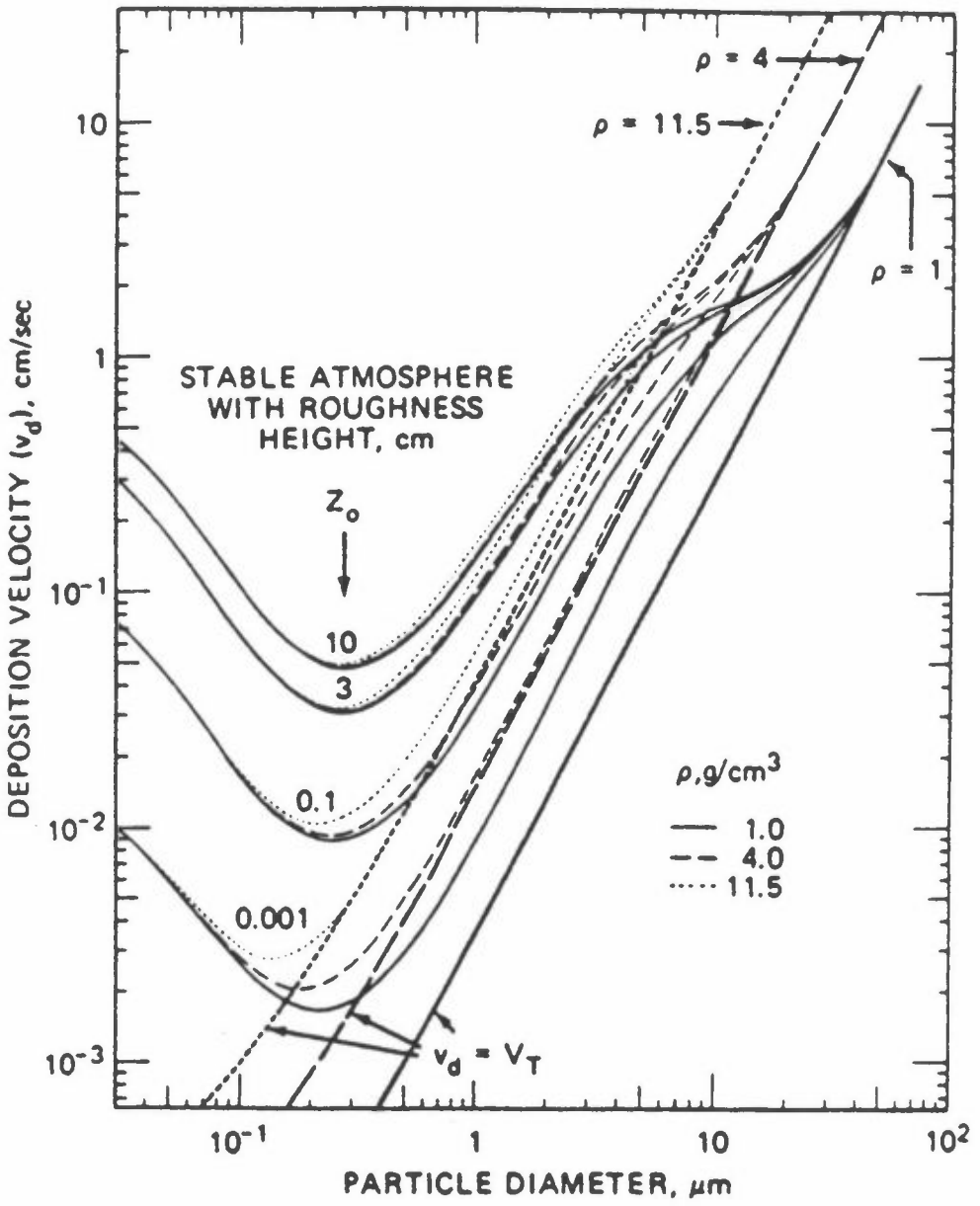


Figure 14: Predicted deposition velocities at 1 m for u_*=50 cm/s and particle densities of 1, 4, and 11.5 g/cm³. (From G.A. Sehmel, Particle and Gas Dry Deposition: A Review, Atmos. Environ., 14:1002 (1980)).

The NILU Gaussian model KILDER applies a partical reflection model where α express the part of the plume in contact with the surface (z=0) that is retaired at the surface as dry deposition ($\alpha = f(v_d, v_t, \sigma_z)$).

The remaining concentration in air is:

$$C = \frac{Q \cdot Ey}{2\pi\sigma_y\sigma_z u}\left[\exp\left[-\frac{(z - h + (v_t x/u))^2}{2\sigma_z{}^2}\right] + \alpha\cdot\exp\left[\frac{-(z + h - (v_t x/u))}{2\sigma_z{}^2}\right]\right]$$

8 THE USE OF AIR QUALITY MODELS

Air quality models have been used for several purposes (see also Fig. 15).

- estimate stack heights at single sources
- evaluate impact from large point sources
- estimate results of emission controls
- accidental release impact
- deposition of aerosols and gases to vegetation
- odour evaluation
- estimate photochemical oxidant potential
- impact of distant sources
- land-use planning
- traffic planning
- planning of measurement programmes
- analyses of measurement data
- episode forecasting
- environmental impact assessment
- implementation plans

An operational dispersion model contains different elements.

In the atmosphere:

- emissions
- meteorology (wind, turbulence, temperatures)
- chemical reactions
- deposition mechanismes

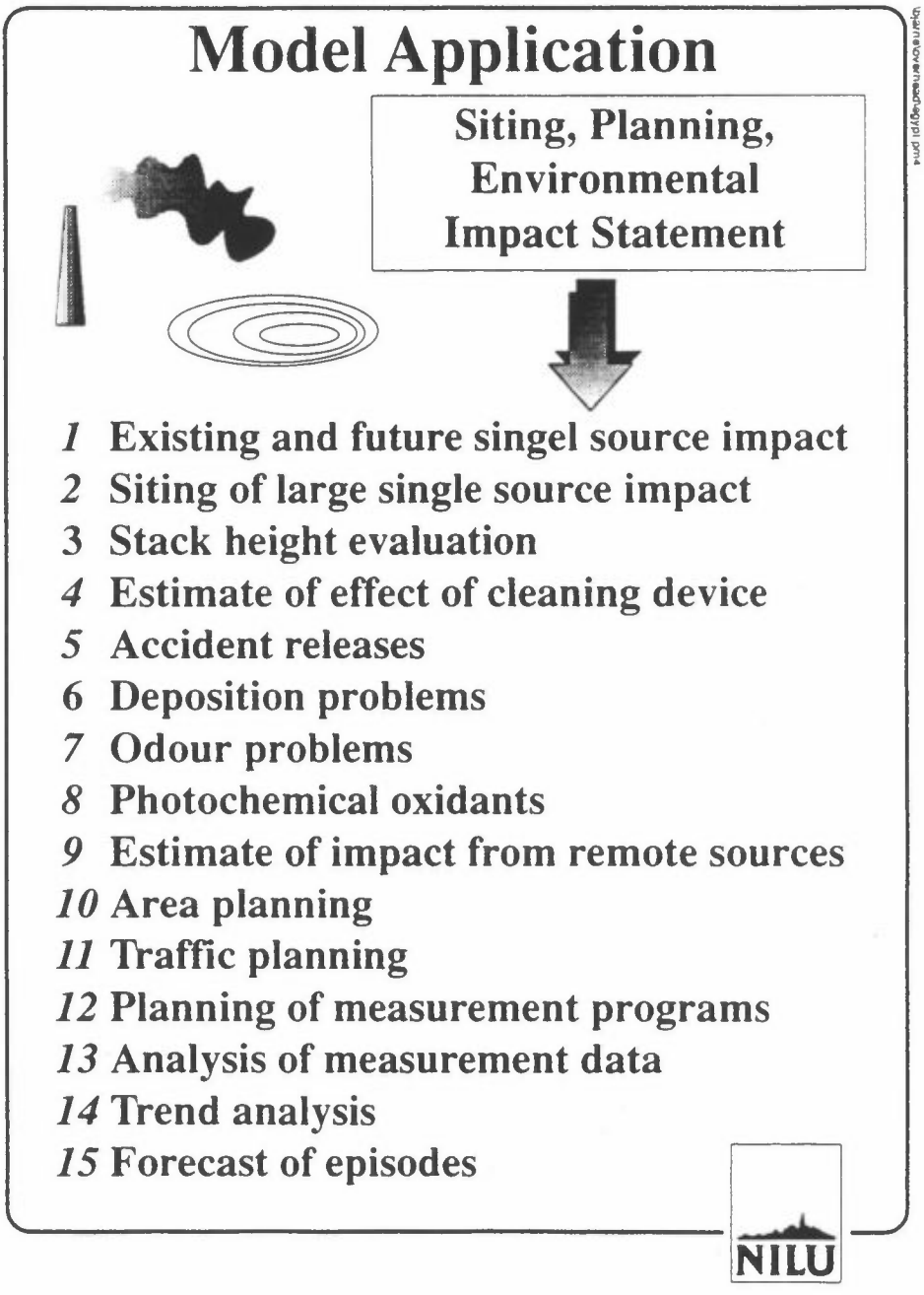


Figure 15: Model application

It contains measurements, evaluation and simulation as shown in Figure 16.

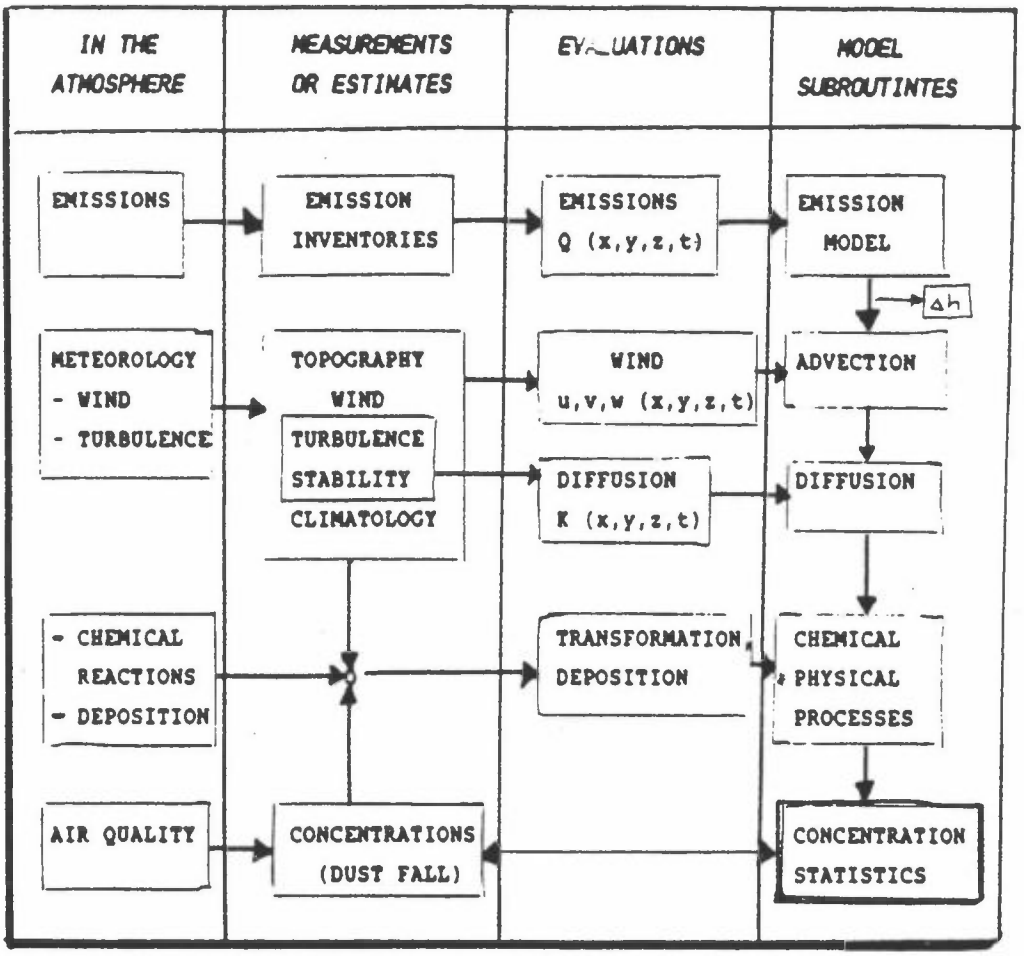


Figure 16: An operational dispersion model.

A dispersion model is in may cases more useful than many measurement programmes. At least together with measured air quality data the model is superior compared to measurement data only.

The selection of what type of model can be based upon the model classification tree (Figure 5) and is dependent upon several factors as shown in Figure 17.

A model produces the complete picture of a concentration distribution for the area. A source oriented model can break the individual sources into part contribution and evaluate the importance of each source to the total exposure.

The model can also be used to evaluate the representativity of measurement data. A first estimate of the maximum ground level impact from stack emissions can be obtained from a simple Gaussian type model (Figure 18).

An example of concentration estimates performed for Bilbao Spain with the short term impact from one single source is shown in Figure 19.

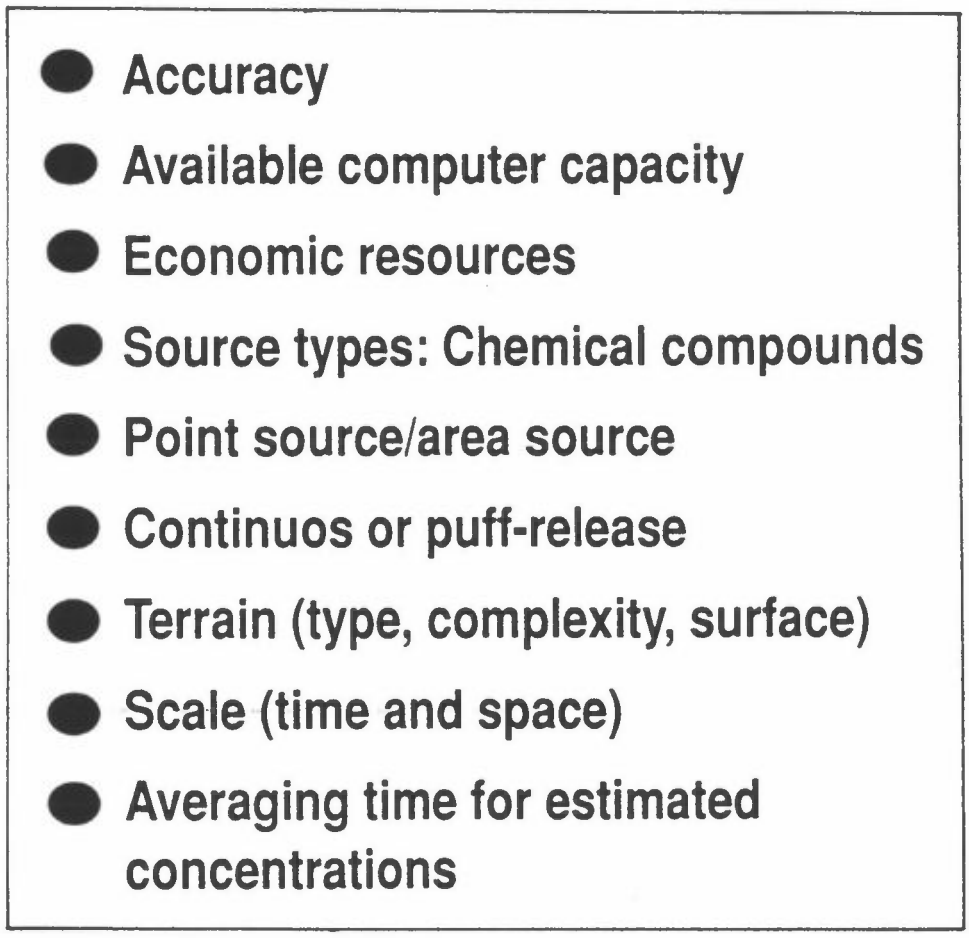
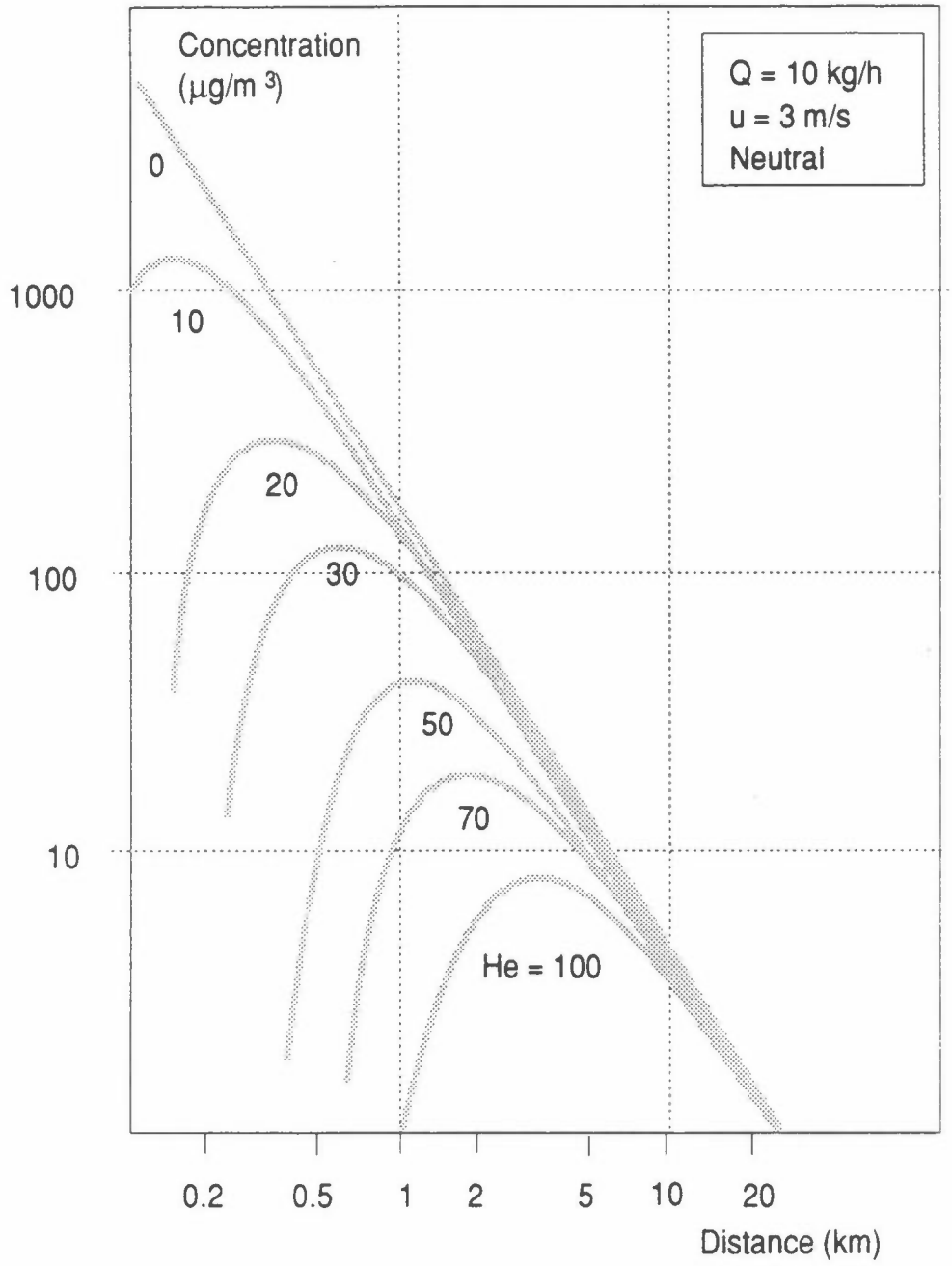


Figure 17: Selection of models.



Concentration at ground level along the wind direction for neutral atmospheric conditions and emissions Q = 10 kg/h
Wind speed u = 3 m/s

(from D. B. Turners Workshop of Atmospheric Dispersion Estimates)

NILU

Figure 18

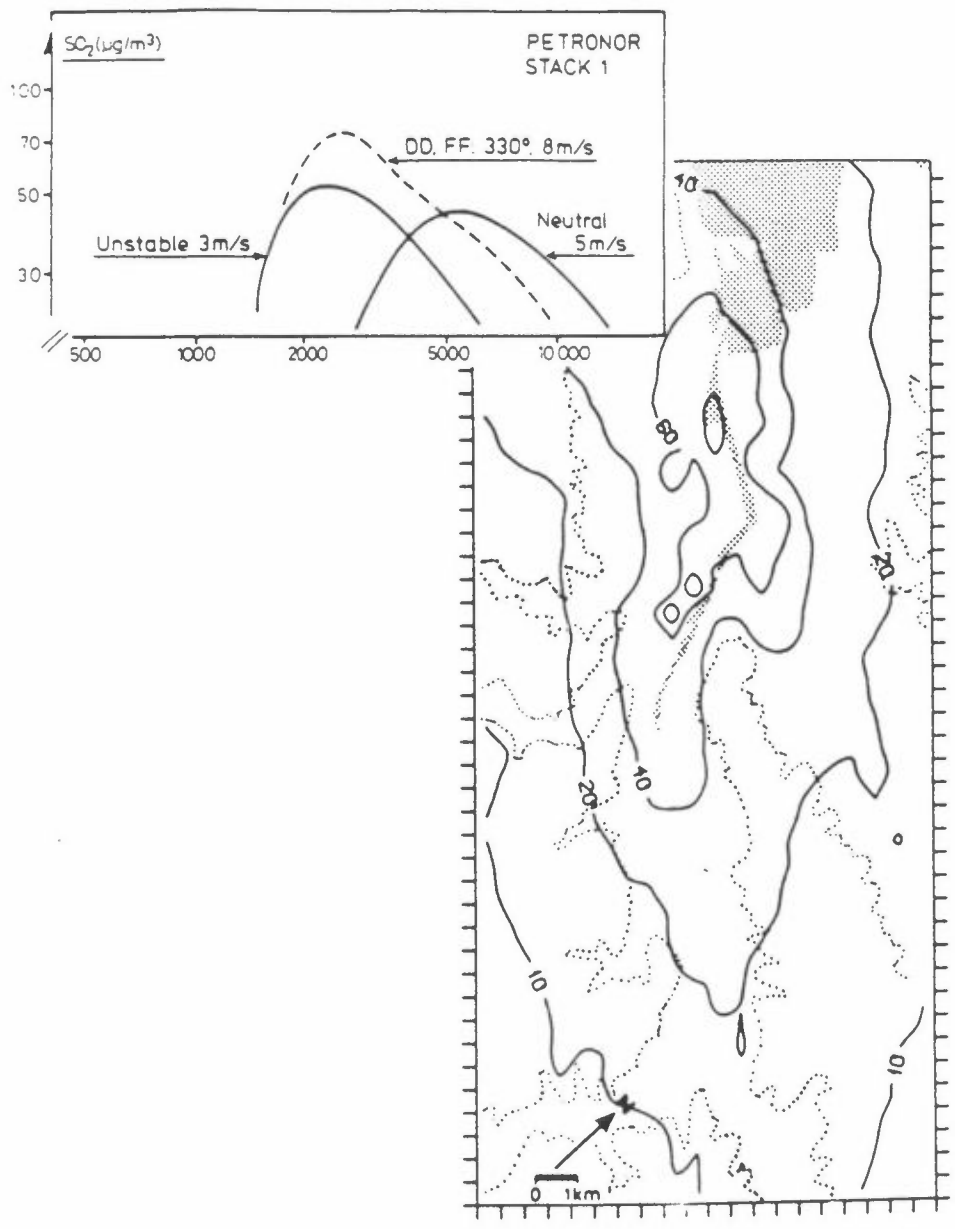


Figure 19: Estimated SO_2-concentrations in Bilbao.
a) Maximum one-hour average conc. as a result of emission from one stack.
b) Annual average concentration distribution from the whole area.

Models have also been applied together with on line measurement of meteorology and air quality to establish automatic alarm systems as shown i Figure 20.

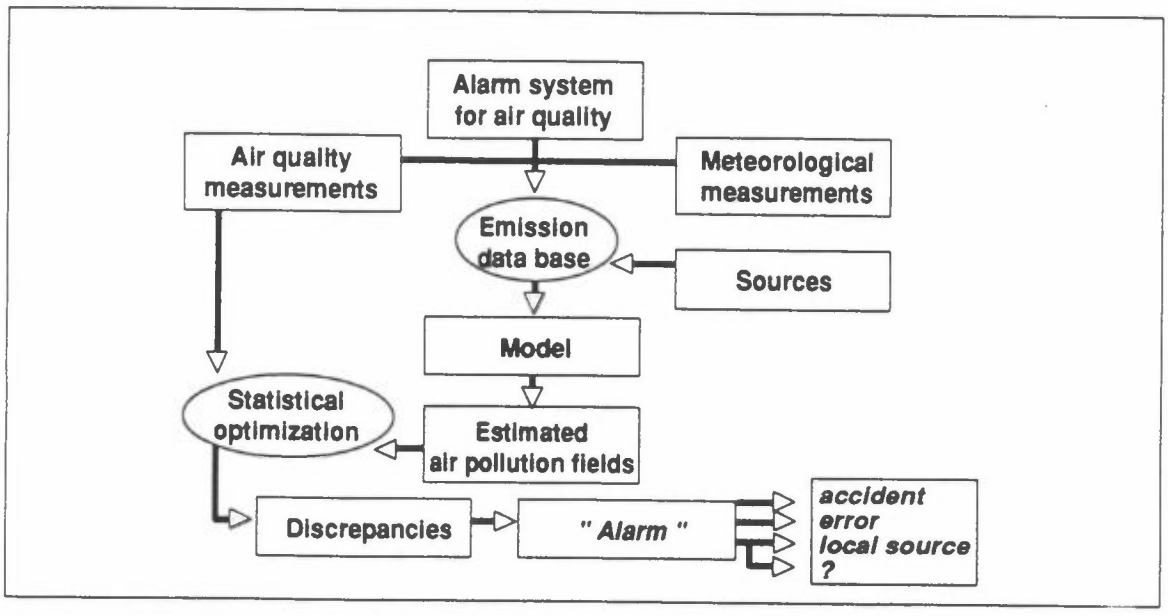


Figure 20: An on line alarm system based upon an advanced dispersion model/measurement system.

From on-line air-quality data and meteorological data transferred to a central computing facility the model can estimate expected air pollution concentration distributions (fields) every hour based upon available emission data.

Graphical display and presentation of the air pollution fields on a data screen can be used to issue information to the public. In Oslo, Norway the on-line continuous air pollution monitoring system alone has been used to issue a daily information and forecast of the air quality through local radio stations. This information was classified in low, medium and high air pollution levels. The levels were related to the WHO Air Quality guidelines.

Discrepancies between model estimated (expected) concentrations and measurements can be used to issue "alarms". The model system will also be used to explain the "alarm", and give information about "local sources", accidental releases at specific sources or impact of adverse meteorological conditions. Such a system has been developed for an industrialized area with two separate urban areas in an industrial region of southern Norway.

Forecasting of high air pollution impact will have to rely upon a forecast of meteorological conditions. A parameterization of these conditions used as input to the model system can give valuable air quality information for air pollution episode forecasting.

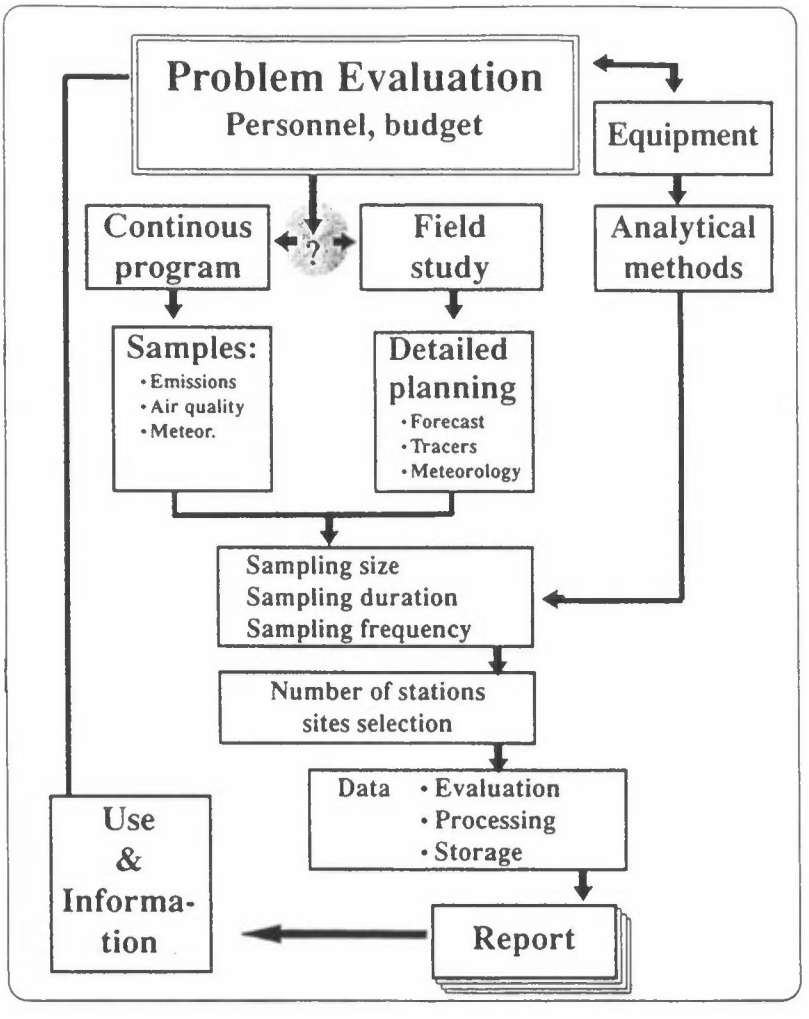
The on-line surveillance and modelling system can also be used to estimate future impact resulting from changes in the emission conditions. It can also, when operative, be used for designing optimal abatement strategies.

NILU F: 14/92

NILU F : 14/92
REFERENCE : O-92014
DATE : MAY 1992

Air Quality Assessment and Surveillance Programmes

B. Sivertsen



NILU

NORSK INSTITUTT FOR LUFTFORSKNING
Norwegian Institute For Air Research
POSTBOKS 64 — N-2001 LILLESTRØM — NORWAY

AIR QUALITY ASSESSMENT AND SURVEILLANCE PROGRAMMES

1 INTRODUCTION

Norwegian Institute for Air Research (NILU) has performed several comprehensive studies of the air pollution situation in urban areas. This paper will summarize the use of air quality models as a planning tool for

- optimal abatement and control strategies,
- environmental impact and effect studies,
- alarm and warning systems.

A model for a total air polution system might consist of:

I Strategy for air pollution control
  a) A.Q. standards
  b) Emission standards

II Source control, concession and control
  a) Control methods
  b) Alternative processes
  c) Cost/effectiveness

III Surveillance and ambient air control
  a) Air quality measurements
  b) Transport and diffusion evaluation
  c) Modelling and exposure evaluation

IV Episodes, forecast and "tactics"
  a) Episode control tactics
  b) Air pollution forecast

This paper summarizes the objectives, contents and requirements for undertaking such a programme.

2 OBJECTIVES

The main objective of an air quality assessment programme can be to:

- provide information on how much air pollution the population is exposed to
- establish a basis for strategies to reduce air pollution
- obtain a basis for estimating environmental impact of further development in the region.

Such studies include the following elements:

- area and land use description
- emission inventories
- air quality measurements
- meteorological measurements
- development and use of dispersion models
- evaluation of the effects of pollution.

3 RECOMMENDED APPROACH

Before going into the content of the assessment programme, let us discuss design and evaluate the content of the programme.

After defining the objectives we have to:

1. Establish a survey for data needed
   - nature and accuracy.
2. Design the sampling programme
   - where, when, how often.
3. Select, test and install equipment.
4. Establish quality control, data handling system.

Only then we can conduct the programme, review results, improve and finalize the analyses.

A diagram for conducting an evaluation of the task for establishing an assessment programme is presented in Figure 1.

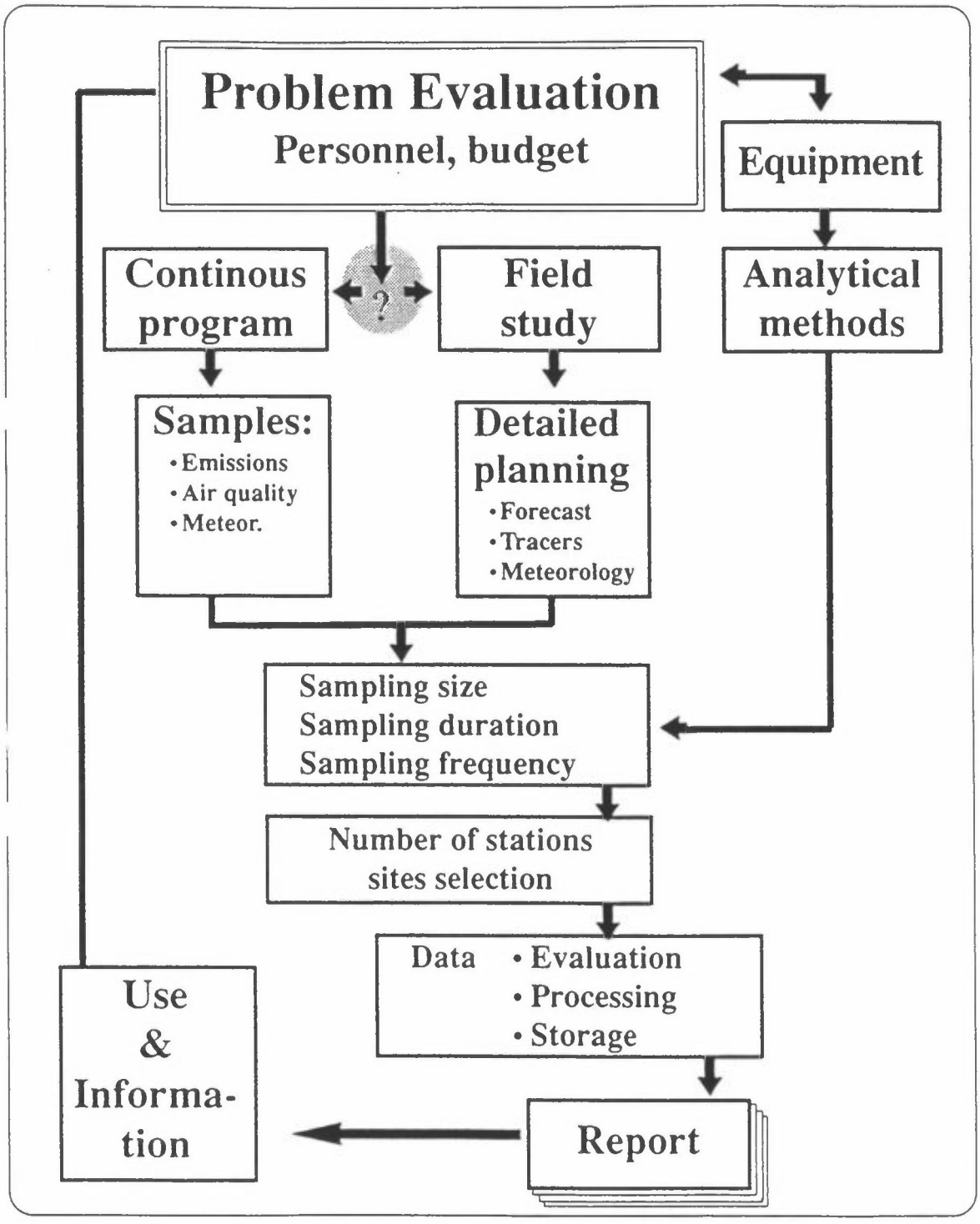


Figure 1: Evaluation for establishment of an assessment and surveillance programme.

4 CONTENTS

The contents or main components of an air quality assessment programme is dependent upon the area, population density, air pollution sources, meteorology and climatology, etc.

It might be necessary to conduct a first screening to classify the problems. When the screening and evaluation phase have given adequate input to the planning and start up of an air quality assessment and surveillance programme the following elements should be included:

- Area and land use description,
- emission inventories,
- air quality measurements,
- meteorological measurements,
- development and test of dispersion models,
- application of models to estimate exposure and impact,
- evaluation of effects,
- impact of alternative strategies.

5 AREA AND LAND USE DESCRIPTION

The characteristics of the geographical area to be studied ect affthe selection of the appropriate assessment programme to a great extent.

The main items to be included in the area description are:

- localization, boundary and grid size of the area

- geographical and topographical characteristics, including:
  - location area, with respect to climate (coastal or inland)
  - typical geographical features (valleys, hills, flat terrain, forests and lakes)

- population distribution

- energy production and consumption distribution

- location of industrial sources, industry areas

- traffic density distribution, major highways and crossings

- land use within the area, e.g. agriculture, recreational areas

- the surrounding areas as far as they may influence the impact inside the assessment area.

6 EMISSION DATA

Air pollution emission inventories for selected pollutants have to be established for the area. The emission inventory yields a specific year of reference, supplemented by additional statistical data, if available.

For assessment programmes the emission inventory is usually established for atmospheric dispersion modelling purposes.

The emission inventories are thus generally composed of three categories of emitters: point, line and area sources. A large fraction of the total emissions usually come from point and line sources.

A distinction must be made between the principal air pollutants of concern. These are usually sulphur dioxide (SO_2), oxides of

nitrogen (NO_x), carbon monoxide (CO), hydrocarbons (HC) and particulates.

Important air pollutants are also formed in the atmosphere from the emissions of NO_x, HC, SO_2, Cl and others.

Specific hazardous pollutants (e.g. asbestos, fluorides, vinyl chloride) are important in land use planning and emission inventories for such species are important to obtain.

The emission inventory should be divided into source categories:

- household and small consumers
  based upon: energy consumption, use of fuel oils, type of heating, population distribution, density of dwellings, emission factors etc.

- transport
  based upon: number of motor vehicles, traffic pattern, driving conditions, emission factors for different type of vehicles, (passenger, cars, trucks, buses..) variation in traffic density with time.

- industry
  based upon: emission measurements, fuel consumption, type of processes, production rate, time variation.

- electricity generation (power plant)
  based upon: fuel consumption, fuel type and emission factors.

- incineration
  based upon: type of furnace, emission control system, emission measurements.

- miscellaneous.

The emission factors are essential when making an emission inventory, because they express the relationship between fuel consumption and the actual release rate for emissions from a specific source category.

The emission inventory data also has to include information about stack heights, gas flow rates, and exit gas temperature.

The details required in an emission inventory is based upon the purpose of the study. The source categories are often specified on a 1 km x 1 km grid. The location of large point sources should be specified more precisely. Emission factors typically apply to domestic heating sources, traffic using petrol or oil and in some cases to other air polluting activities.

For the collection of data about emissions, especially industrial processes, large power plants and incinerators, questionnaires have been developed and widely distributed within the assessment area.

7 AIR QUALITY MEASUREMENTS

An extensive record of the air quality is important in a survey. This should include information on the variations in pollutant concentrations in time and space. Variations in time may be diurnal, seasonal, and annual. In large studies, it is desirable to use an air sampling network in and around the area of interest. The design of such a network will depend on available resources. Its configuration should take into account the sources, receptors and local climatology. The amount of data to be collected and the detail and accuracy required is influenced by the final goals of the study.

Air quality models are useful in both the planning, design and final analysis of such networks. If measurements are to be used in the regulatory process, it must be shown that they are re-

presentative. Air quality models provide a method of testing the relevance of the monitored data.

The air pollution components to be studied are dependent upon the activitiy in the specific area, and upon air pollution impact concern or regulations (air quality standards). Both primary pollutants such as (SO_2, NO_x, HC, and particles) and secondary pollutants (ozone, NO_2, SO_4, etc...) should be considered.

The data collection is determined by the space and time resolution that is needed, which again is determined by the resolution of the effects that will be examined.

In the design of the monitoring programme a basis for the data analysis and presentation is given, and it should be possible to answer specific questions about the air quality in the region.

The following information should be supplied:

- mean daily concentration for all pollutants
- diurnal variation of selected pollutants
- the frequency distribution of the concentrations
- maximum values (hourly, daily)
- the major sources for the concentrations found at the receptor points.

The data can be collected using fixed monitoring stations, mobile sampling units or remote sensing. A combination of these techniques are often applied. Model calculations can explain how representative the data are and can give a picture of the concentration distribution also in areas where measurements are

not carried out. For this purpose meteorological data are also needed.

8 METEOROLOGICAL AND CLIMATOLOGICAL DATA

Concentrations of air pollutants vary in space and time because the sources are scattered and the local meteorology varies due to topography and the large scale weather. To collect information about meteorology and climatology in an area at the same time as air quality data are collected is therefore crucial for analysing and understanding the problem.

Coastlines, valleys or escarpments indicate that mesoscale winds may occur. Site inspections may help to confirm the existence of such flows. Mesoscale circulations often have a day-night reversal, and the wind roses are most informative when they have been prepared separately for daylight and night-time hours, or even better on an hourly basis.

The following meteorological observations may be useful:

- Wind speed and direction measured at meteorological towers (of at least 10 m). The number of measurement stations should be sufficient to determine the wind field within the study area, and should be located so that they can be used to estimate transport and diffusion. Winds at some elevation above the study area should be available (observed in a television tower, using radiosondes, acoustic sodar systems or from geostrophic wind information).

- Air temperature should be measured to establish the variation in space (horizontally and vertically).

- Air temperature differences (profiles) with height should be measured directly to provide information about atmospheric stability conditions.

- Turbulence measurements are essential to estimate dispersion of air pollutants. This can be accomplished by measuring 3-component wind speed fluctuations or wind direction fluctuations. Estimates of turbulence can be undertaken from measurements of vertical temperature gradients and wind speed. Also indirect but less accurate methods for estimating turbulence from other climatological data are available.

- Relative humidity should be measured to explain visibility and humid plumes.

- Precipitation amounts, intensity and chemical composition should be available to estimate wet deposition.

- Mixing heights (from vertical temperature and wind profiles data, radiosondes) should be collected at least once at daytime and once during the night. In some cases mixing height could also be estimated from sodar-data, or from surface data on wind speeds and surface heat fluxes.

9 AIR QUALITY DISPERSION MODELS

Air quality models are used to establish the relationship between emissions and air quality. Meteorological data and knowledge of physical and chemical reactions in the atmosphere are used to calculate the air concentrations of one or more species as a function of time and space.

Calculations of atmospheric dispersion depend on input data, representative dispersion parameters and sufficient meteorological information to estimate the turbulent conditions in the atmosphere. In the following list, the data necessary for model calculations are given.

Emission and source data:

- source location, i.e. geographical co-ordinates
- source dimensions, i.e. height and exit diameter
- exhaust gas exit temperature and velocity (or total volum flow rate)
- mass flow of air pollutant from the source
- time dependence of pollutant emission, i.e. duration, frequency as well as diurnal and seasonal variations.

Transport and dispersion data:

- hourly averaged wind speed and direction
- description of atmospheric turbulence and stability (to estimate dispersion)
- mixing height
- height of inversion layers
- ambient air temperature (for plume rise calculations)
- joint frequency distribution of at least first three meteorological parameters.

The type and complexity of the air quality model will depend upon:

- source characteristics
- type of pollutants to be estimated (primary, inert, secondry, gas or particles)
- size of the area
- topographical features computer
- economy.

In Figure 2 is indicated the elements in an abatement strategy model based upon an air pollution dispersion model.

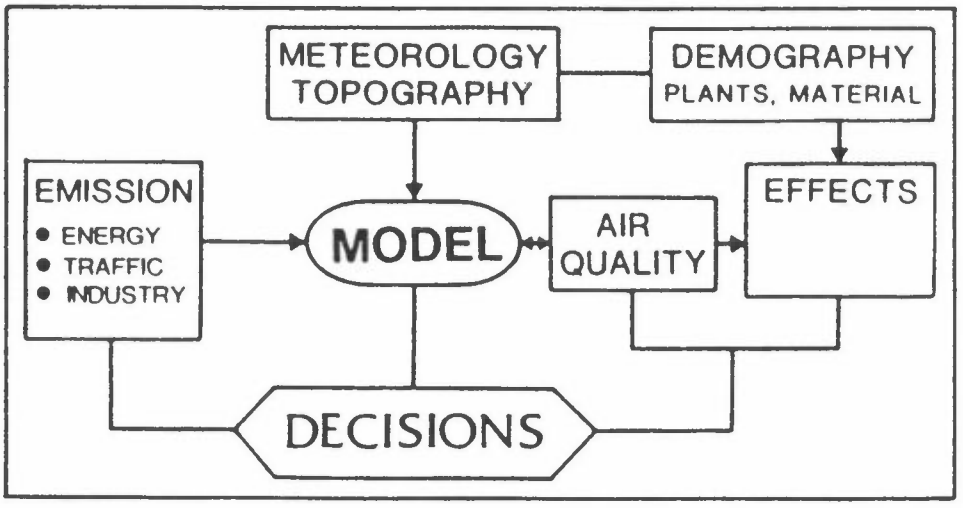


Figure 2: The elements in air pollution dispersion model simulation.

Many types of air pollution dispersion models are available. Some of them have also been developed and applied at NILU. In principal, source oriented models can be divided into deterministic models and statistical models.

Statistical models ("roleback models") estimate concentrations from empirical statistical relationships between air quality and meteorology. These models are used to estimate air quality in a given meteorological condition, assuming that the emission pattern is unchanged. For short term forecast used in operational air quality control programmes, these models have been widely used. They are, however, not suited for long term planning.

Deterministic models calculate concentrations from emission-inventories and meteorological data with mathematical equations for the physical processes.

Most deterministic models are based upon solutions of the diffusion equation.

In steady state models a fixed concentration distribution varying in space for a given meteorological situation is calculated. Such models are:

- gaussian point source models for estimating impact from stacks

- multiple source gaussian models for point and area sources in urban areas

- simple area source models based upon a input/output (flux) consideration where the concentrations are inversely proportional to the wind speed.

In time dependent models all variables can be functions of time and the concentration output is also dependent. Such models are:

- box models for urban areas to estimate the flux of pollutants across boundaries of boxes where account of sources, dispersion, deposition and transformation is taken.

- grid models usually solve the diffusion equation numerically in a grid. A large number of grid models exist for solving different specific problems, also including photochemical processes.

- Lagrangian (puff trajectory) models where puffs of pollutants are advected along the wind trajectory and where diffusion, transformation and deposition take place.

Several other air quality models exist, but it is believed that the commonly used source oriented models for air quality assessment programmes are mentioned above.

Receptor models are different from the source oriented models as they are based on mathematic/statistical evaluations of air quality data collected in a receptor point. These models can be used to estimate the relative importance of different source categories to the contribution of pollutant at a measuring point. These models are considered useful in the analysis of existing air quality data and the verify source oriented model performance.

10 AIR QUALITY ABATEMENT STRATEGY

The contribution of air pollution from vehicular traffic, home heating and industry to the population exposure in an urban area can be calculated based upon data for emission, dispersion and residential distributions.

The calculations are carried out in a 1 km^2-grid with special calculations for roads with high traffic and for large point sources. Based on data for pollution advection into each km^2, on local contribution and on the concentrations close to streets with high traffic, estimates are made of the cumulative spatial distribution of air pollution within each km^2.

An abatement strategy model with input/output data relevant for taking decisions concerning the best abatement strategies is shown in Figure 3.

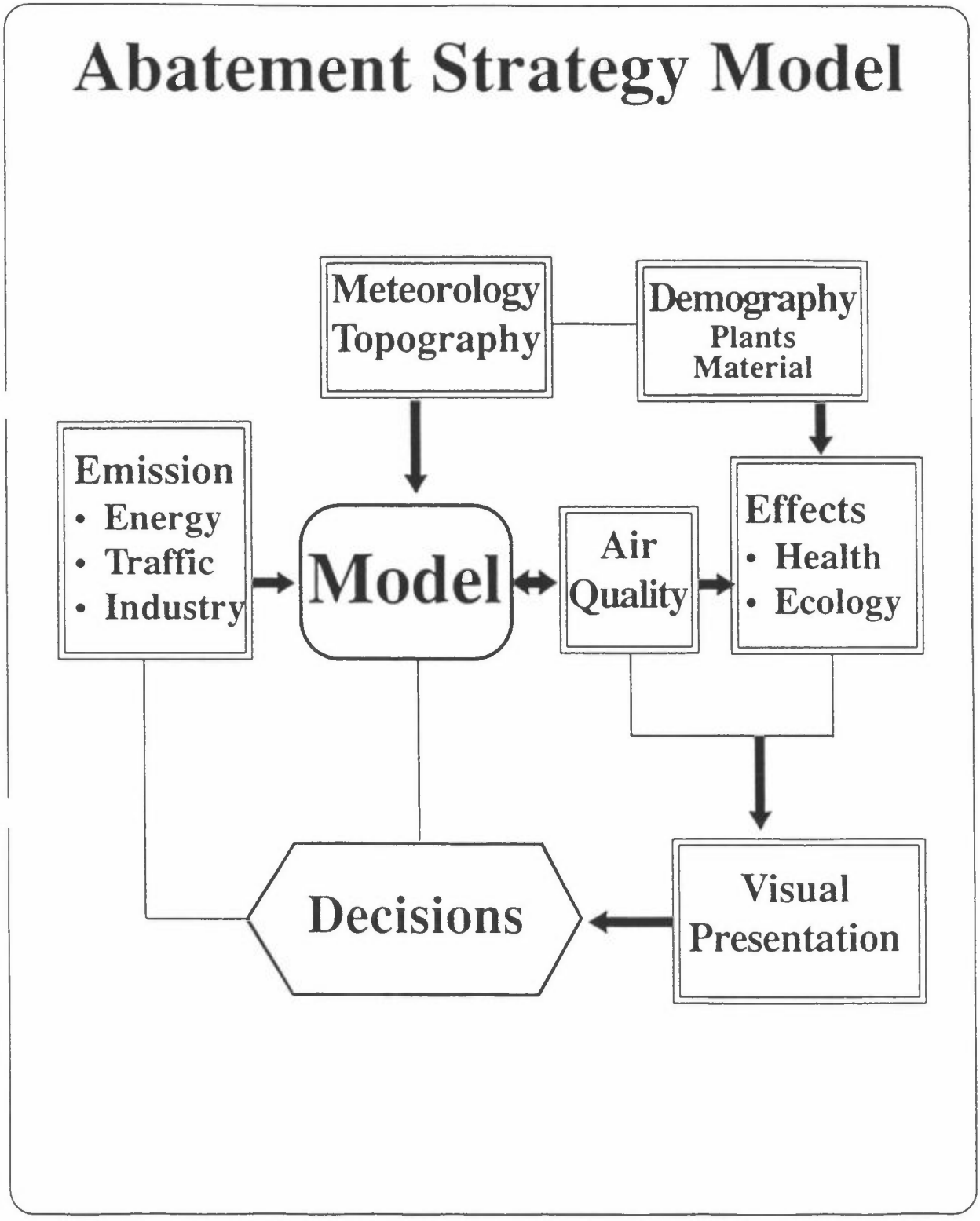


Figure 3: An abatement strategy model

The number of people living in each km^2 combined with the concentration distributions are used to summarize the population exposure to 24 hour mean episodic concentrations values.

Population exposure curves for SO_2, NO_2, CO and particulate matter has been used to evaluate future air quality as a result of alternative emissions situations.

The local air pollution concentration in an urban area consists of the following additive contributions:

- the contributions from neighbouring square-km areas: C_o
- contribution from local street emissions: C_g
- contribution from other sources within the square-km: C_a.

The concentrations within a street (C_g) are calculated by the street canyon model and the concentration from the area sources are calculated by the square-km model ($C_b = C_o + C_a$). (See Figure 4).

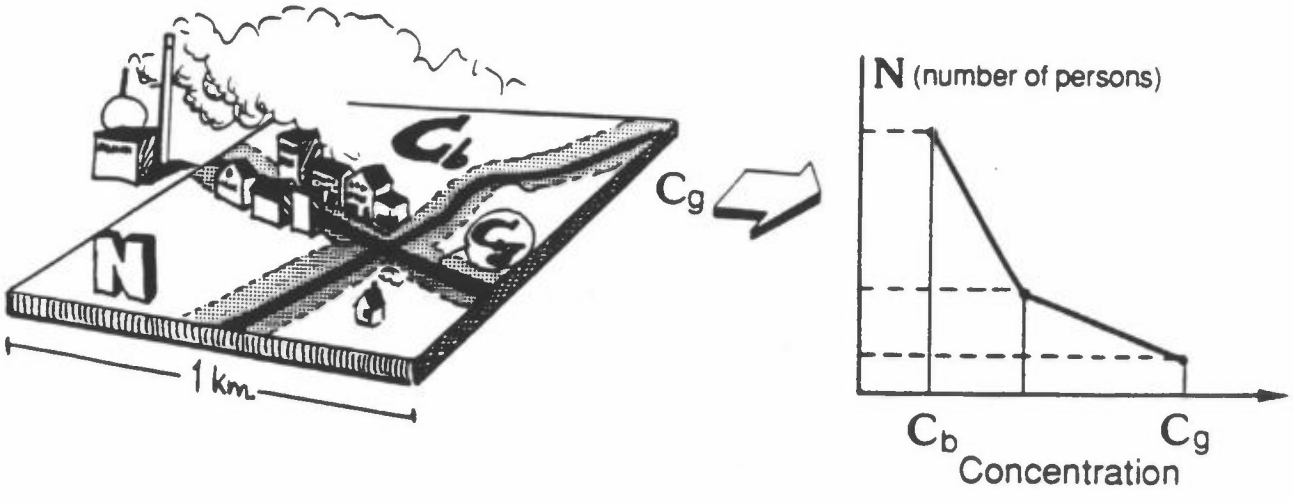


Figure 4: Estimated number of people living in areas where the pollution concentration is higher than the values given along the horizontal axis.

The spatial concentration distribution within each square-km is characterized by a minimum concentration that all people are exposed to and a maximum concentration affecting only few people. The background concentration (C_b) is calculated by the square-km model. In this way two points on the cumulative exposure curve are determined. A third point is found by calculating the area of the zone around local streets where the concentration exceeds the area source contribution (C_b) by 40 per cent of the maximum street concentration from local street emissions. When developing the simplified model it was found that the 40% concentration value gave a reasonable approximation of the exposure curve as shown in Figure 3. When the population exposure is summarized for the area, the curve become continuous and represents a combination of models on two different scales.

These types of models can then be used directly to compare alternative abatement measures against the environmental impact on humans (health) by comparing to the number of people exposed to certain concentration values (AQG) for each strategy. These "impact"-values can also be compared to costs to give a cost/impact ratio as a basis for priorities (see the Oslo case in 11.2).

11 EXAMPLES OF SURVEILLANCE AND ASSESSMENT PROGRAMMES

11.1 SURVEILLANCE OF AIR QUALITY IN BILBAO, SPAIN

Norwegian Institute for Air Research (NILU) carried out a surveillance programme of air quality in Bilbao, Spain. The investigations started in December 1985 and was performed for the Basque Government.

The study contained:

- A statistical evaluation of historical data from 1979.
- Establishment of the statistical programs at LABEIN.
- Single source and multiple source models prepared and delivered.
- Emission inventories and single source dispersion estimates.
- Evaluation of 1986/87 air quality and meteorological data.
- Multiple source modelling of long term average SO_2-concentration.

A brief summary of results includes the following statements:

- Local seasonal and diurnal cycles of wind and stability indicated that stable down valley drainage winds were predominant during winter and at night. Unstable and neutral conditions prevailed in strong sea breezes (up valley winds) during day time, especially in the summer season.
- The average SO_2-concentrations in the area decreased considerably from 1979 to 1986.
- Seasonal average SO_2-concentrations in excess of 60 $\mu g/m^3$ only occurred at the coast in summer and in Bilbao city in winter.
- One hour average SO_2-concentrations exceeded 300 $\mu g/m^3$ at 3 stations but never more often than 2% of the time. SO_2-concentrations of 400 $\mu g/m^3$ or more only occurred 0.4 to 1% of the time throughout the year.

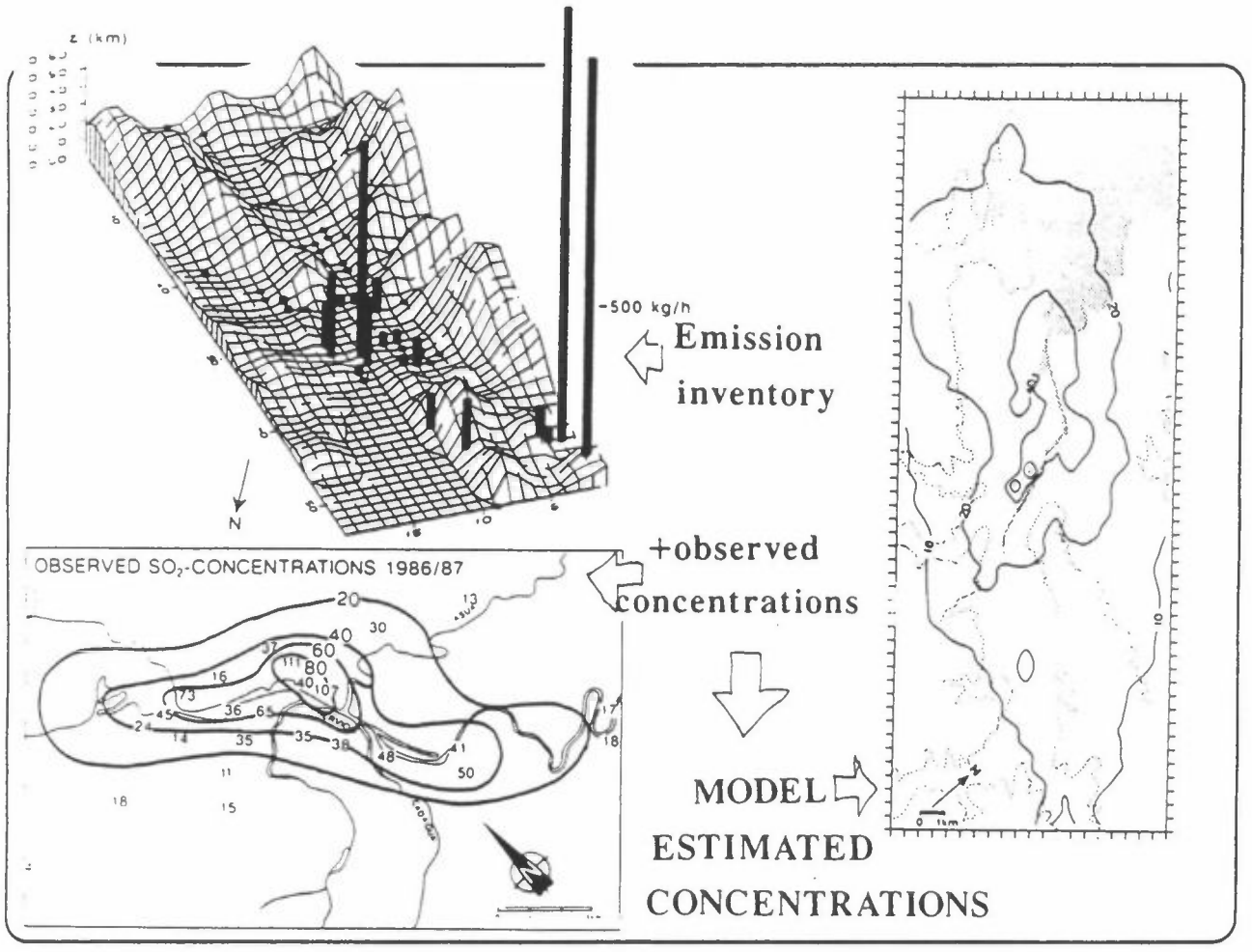


Figure 5: Concentration distributions (annual, seasonal, hourly) in Bilbao were estimated based upon emission inventories and measurements of meteorology and air quality.

- Air pollution episodes occurred 4 to 8 days each season. Characteristic for these episodes were weak variable down valley winds in winter conditions, or land sea breeze situations in summer.

- Emissions from industrial point and area sources, contributed 60% and 20%, respectively, to the total SO_2-concentrations in the area. Domestic heating and traffic represented about 10% each on an annual basis. Model applicataion for planning purposes is demonstrated. In a highly polluted area, the exclusion (cleaning) of two sources could reduce the impact from around 70 $\mu g/m^3$ to 35 $\mu g/m^3$.

11.2 ABATEMENT STRATEGY STUDY IN OSLO, NORWAY

The Norwegian State Pollution Board initiated an abatement strategi study in Oslo to evaluate the benefit of improved air quality versus the cost of different emission reductions. A total of 38 measures were evaluated with respect to improvement of air quality in Oslo year 2000. The basic alternative was no change in activity except for introduction of catalytic converters installed in new gasoline cars from 1988.

The maximum concentration levels included in this study are representative for a cold winter day in Oslo when the emissions are captured beneath an inversion layer which cause high impact of air pollutions. The air quality guidelines used for the components considered are 50 $\mu g/m^3$ for soot and 100 $\mu g/m^3$ for SO_2 and NO_2.

The basic alternative for year 2000, with no emission reduced activities included except for catalytic converters for cars, gave that about 184 000, 150 000 and 12 000 persons were exposed for concentrations above air quality guidelines for SO_2, soot and NO_2, respectively.

To perform a cost/benefit priority of the 38 different measures, the evaluation of cost of each measure had to be carried out. The combined effect of cost and benefit gave the ranking given in Table 1 below.

Table 1: Ranking of the most important measures from the Oslo abatement strategy study.

		N persons (1 000)		
		SO_2	Soot	NO_x
	No measures	184	150	12
1	Buses, reduce emission	184	147	11
2	Diesel car maintenance	184	127	11
3	No heavy oil in winter	137	121	11
4	Diesel cars, emission reductions	137	115	10
5	Idling	137	115	10
6	Wood burning	137	76	10
7	More electricity	137	72	10
8	Reduced sulphur in oil	13	72	10
9	No open burning	13	72	10
10	Diesel trucks, reduced emissions	13	54	9
11	Traffic systems	13	43	1
12	City buses, reduced emissions	13	42	1
13	Central heating, maintenance	12	41	1
14	Improved cleaning of roads	12	41	1
15	Central heating, expansion	4	34	1
16	Needle tyres, restrictions	4	34	1
17	Energy optimalisation	3	34	1
18	Industrial, reduced emissions	3	34	1
19	Heavy diesel trucks, reduced emissions	3	8	0
20	0.5% S in oil	0	8	0

The table shows that the most effective measure to reduce the impact of sulphur dioxide is to reduce the sulphur content in oil. However, this act was quite expensive and therefore was placed at rank 8. Some restrictions due to wood burning in small furnaces will reduce the soot impact considerably. Introducing emission regulations on buses have the lowest cost and reduced the soot impact, so this measure was therefore placed as the first cost benefit activity to be performed.

When introducing the twenty measures given in Table 1, the air quality impact problems in Oslo were reduced with about 90%. In addition, the benefit of introducing the activities will result in a cost benefit of about 100 000 US dollars per year.

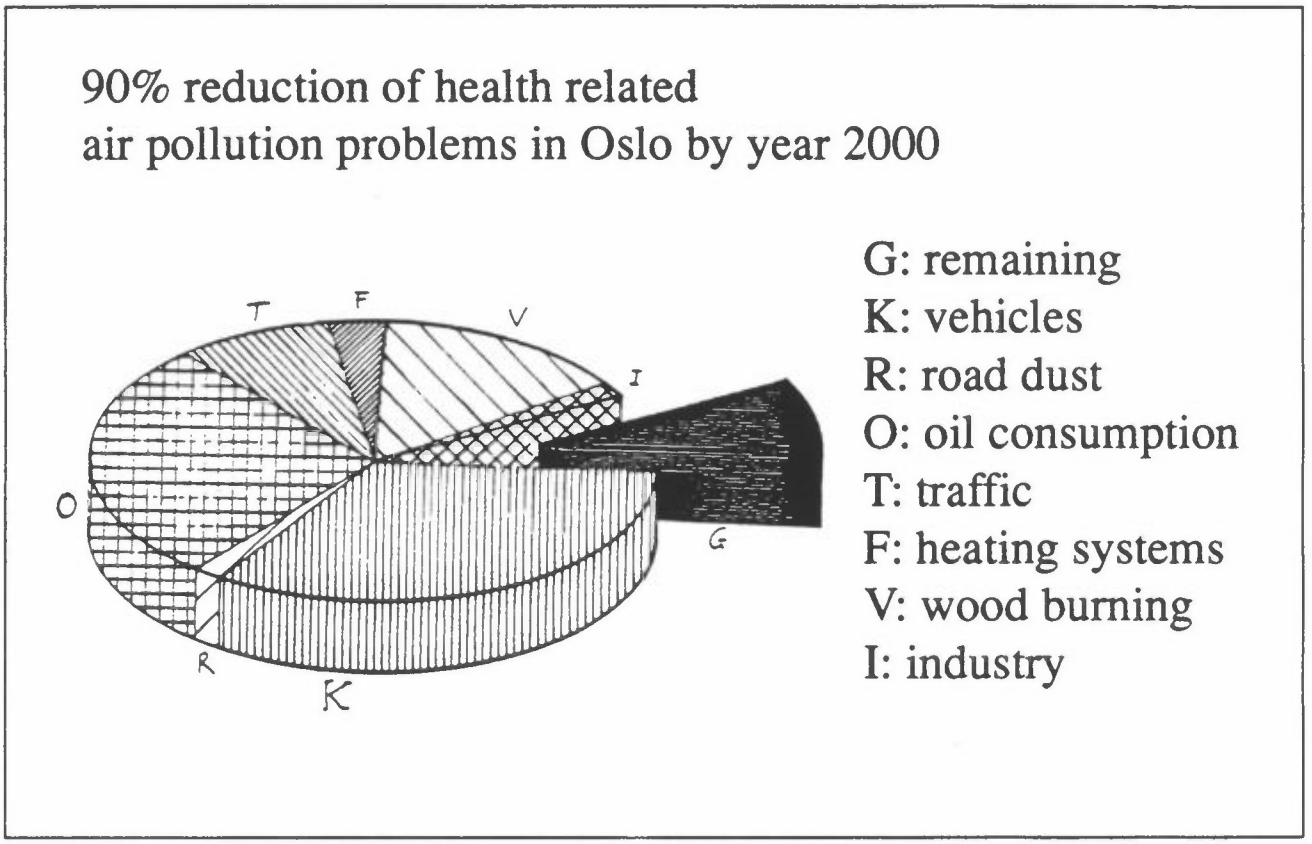


Figure 6: The air pollution problems in Oslo by year 2000 will mainly be due to vehicles, oil consumption, traffic and wood burning. If the ranked measures in the abatement strategy study is taken into account only 10% of the problems will be remaining.

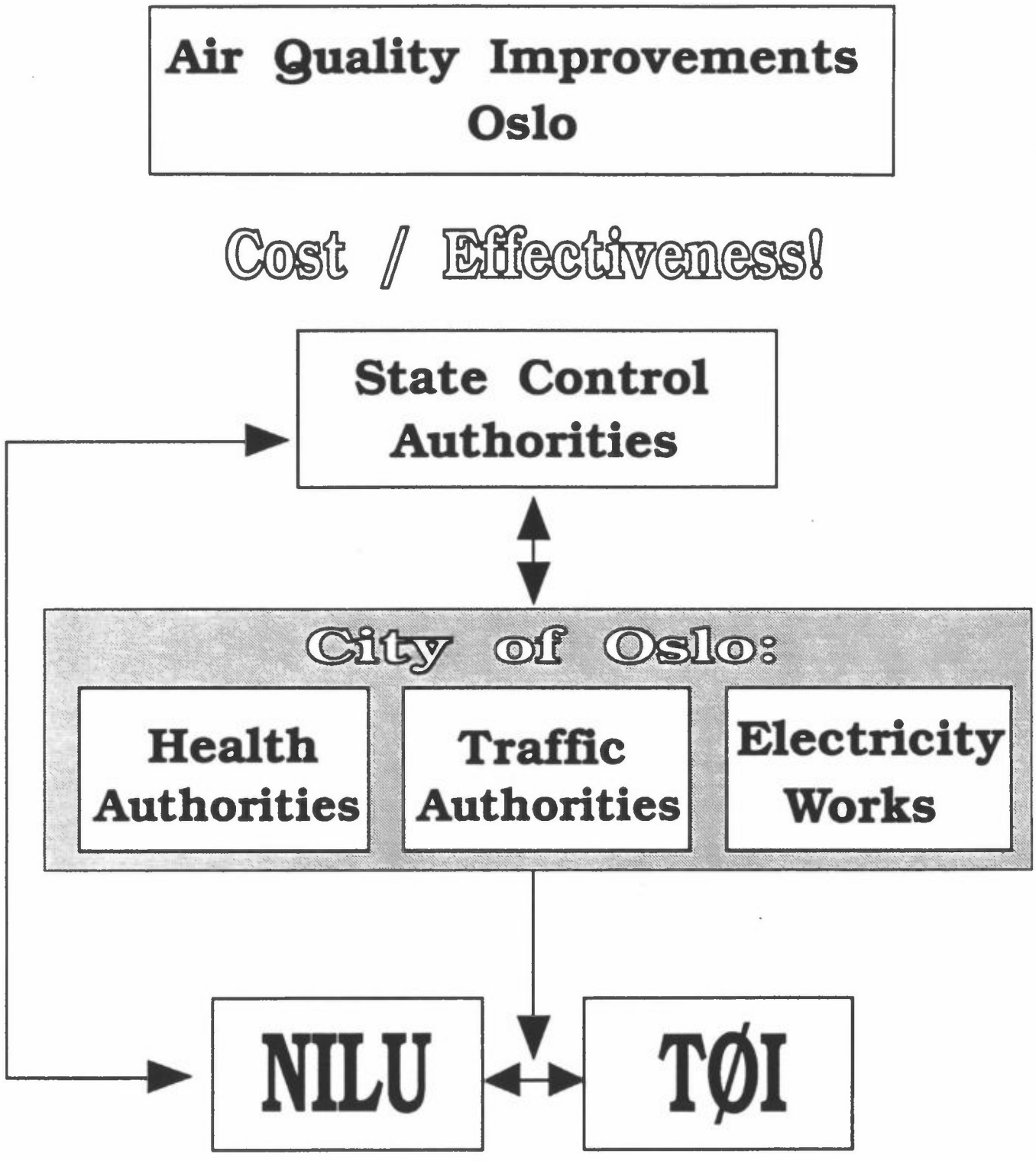

Air Quality Improvements
Oslo
Cost / Effectiveness!
State Control
Authorities
City of Oslo:
Health
Authorities
Traffic
Authorities
Electricity
Works
NILU
TØI

Figure 7

OSLO

How bad was it?

Number of persons in areas where A.Q. criterias were exceeded (1985)

- SO_2 : 30-50 000 persons
- Soot : 60-100 000 persons
- CO : 10-15 000 persons
- NO_x : 20-40 000 persons
- Pb : < 3 000 persons

Figure 8

OSLO

What can we do?

- **Less traffic (individually)**
- **Better public transportation**
- **More effective traffic system**
- **Oppose spiked tires in winter**
- **Desentralized heating**
- **More electricity (hydro)**
- **Reduce sulphur content in fuel oil**
- **Restrictions on industrial releases**
- **Waste incinerating (emission reductions)**

Figure 9

Norwegian Institute for Air Research
Norsk institutt for luftforskning (NILU)
P.O. Box 64, N-2001 Lillestrøm - Norway

REPORT SERIES TECHNICAL REPORT	REPORT NO. 4/93	ISBN-82-425-0491-1	
DATE 30/8-93	SIGN. P.Berg	NO. OF PAGES 185	PRICE NOK 215.-

TITLE Air Pollution Modelling. Sources - Meteorology - Air Quality	PROJECT LEADER Bjarne Sivertsen
	NILU PROJECT NO. O-92014
AUTHOR(S) Bjarne Sivertsen	CLASSIFICATION * A
	CLIENT'S REF.

CLIENT
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ABSTRACT

NORWEGIAN TITLE

DESCRIPTORS Air Quality	Modelling	Meteorology

ABSTRACT (in Norwegian)

* *Classification*
- *A Unclassified (can be ordered from NILU)*
- *B Restricted distribution*
- *C Classified (not to be distributed)*