KONINKLIJK NEDERLANDS METEOROLOGISCH INSTITUUT
MEDEDELINGEN EN VERHANDELINGEN

AN ANALYSIS OF DUST MEASUREMENTS IN THREE CITIES IN THE NETHERLANDS

BY DR. F. H. SCHMIDT

ROYAL NETHERLANDS METEOROLOGICAL INSTITUTE

PREFACE

The ever increasing industrialization and urbanization in the Netherlands requires all efforts of scientists, technicians and authorities concerned to combat the damaging effects of contamination of the atmosphere. The study of the mechanism of distribution and concentration of airpollution is primarily a study of the dynamics of the atmosphere and the effects of the many external and internal influences on the horizontal and vertical motion of air in particular areas. This applies both for pollution of a gaseous nature as well as for pollution consisting of solid or liquid particles, originating from isolated chimneys or from the many sources that are found in densely populated and industrial areas.

In the present study an analysis has been made of the relation between meteorological aspects and the concentration of fine dust in the air in Rotterdam, Delft and The Hague. For that purpose the results of the measurements of dust quantities were kindly put at the disposal of the author by the Food Inspection Department in Rotterdam and by the Research Institute for Public Health, T.N.O.

The Director in Chief
Royal Netherlands Meteorological Institute,
C. J. WARNERS

VOORWOORD

De ook hier te lande steeds toenemende industrialisatie en urbanisatie hebben tot gevolg, dat men op vele plaatsen in Nederland wordt geconfronteerd met het verschijnsel luchtverontreiniging.

De horizontale en verticale verspreiding van deze verontreiniging in de atmosfeer is uiteraard in belangrijke mate afhankelijk van de meteorologische omstandigheden. Dit geldt zowel voor gasvormige als voor uit vaste of vloeibare deeltjes bestaande verontreiniging; zowel voor die welke afkomstig is uit geïsoleerd staande schoorstenen als die welke in de atmosfeer wordt gebracht door de vele bronnen, die zich in dichtbevolkte en industriële centra bevinden.

In de onderhavige publikatie is een analyse gemaakt van het verband tussen de meteorologische omstandigheden en de concentratie van fijn stof in de buitenlucht in Rotterdam, Delft en 's-Gravenhage. De resultaten van de stofmetingen werden daartoe welwillend ter beschikking van de schrijver gesteld door de Keuringsdienst voor Waren te Rotterdam en de Afdeling Gezondheidstechniek van T.N.O.

De Hoofddirecteur van het
Kon. Nederl. Meteorol. Instituut,
C. J. WARNERS

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INTRODUCTION

Theoretical as well as experimental investigations with respect to meteorological influences on the behaviour of air pollution have thus far for the greater part been restricted to point sources. (See e.g. F. PASQUILL, 1962). Notably the behaviour of air pollution in cities has only been considered in relatively few cases. The principal reasons for this may be the following:

Firstly, observations of pollution concentrations in cities are comparatively scarce. As far as available it is mostly average concentrations over 24 hours or even longer periods that have been measured. (H. GRISOLLET and J. PELLETIER, 1957; E. WEISS and J. W. FRENZEL, 1956). Sometimes more or less continuous measurements have been restricted to certain periods of the day (e.g. WAINWRIGHT and WILSON, 1962).

Secondly, theoretical investigations with respect to the behaviour of pollution in cities are in general of a limited scope. FRENKIEL (1954 and 1957) made a plea for the application of highspeed computors to the problem of area pollution. D. H. LUCAS (1958) applied Sutton's diffusion model to the problem of diffusion of pollution originating from domestic chimneys, all of them having the same height. This method is only applicable to situations with at least moderate winds, and it does not permit of determining the effect of meteorological conditions during quiet anticyclonic situations, these being the ones that cause as a rule the most dangerous contamination of city air.

The latter problem has been investigated by D. J. BOUMAN and the present author (1961) who found that after a sudden increase of stability has taken place, concentrations of pollution in a city will increase proportionally with the square root of time elapsed since the stability change occurred. This theoretical result depends on the availability of pollution sources at the ground and was confirmed by the SO_2-increase found in London in December, 1952 and in a case during calm weather in Philadelphia (F. D. DAVIS JR., 1962).

The existence of ground sources in large cities is now generally recognized. According to GRISOLLET and PELLETIER (l.c.) e.g. in Paris about 50% of the total smoke originates from domestic heating, between 30 and 40% from motor traffic (probably Diesel engines) and only 10 to 20% from industry, these figures representing average values over the year.

Similar estimates made by L. J. BRASSER (1958) for the dust sources in the industrial area along the waterway connecting Rotterdam with the North Sea (including the cities of Rotterdam, Schiedam, Vlaardingen and Maassluis) resulted in 51%, 19% and 30% respectively, where the second figure is composed of 3,5% from road traffic and 15,5% from shipping. From the same publication the percentages for the region occupied by the cities of The Hague, Delft, Rijswijk and Voorburg are found to be 77%, 4% and 19% respectively. Although there are differences between the three examples quoted, it is clear that domestic heating is the most important smoke source in all cases and that low lying sources must not be neglected.

Since 1957 two-hourly measurements of the dust content of the air have been made in the city of Rotterdam and from 1960 on also in The Hague and Delft, all three cities belonging to the most densely populated part of the Netherlands, Rotterdam having some 750.000 inhabitants, and more than 820.000 if we include nearby Schiedam; The Hague, including Rijswijk and Voorburg, some 700.000 and Delft some 75.000.

Measurements in Rotterdam were performed by the Food Inspection Department, in The Hague and Delft by the Research Institute for Public Health, T.N.O. In total the observations made in Rotterdam during almost the whole of the years 1957 and 1958 have been analyzed as well as the measurements made at two places in The Hague (September 10, 1960 – October 12, 1961 and December 8, 1961 – May 15, 1963, respectively) and those made in Delft from April 26, 1961 – July 5, 1962 inclusive. See for the observations made in The Hague and Delft: L. J. BRASSER, 1963, a, b and c.

In the present paper the results of these observations are studied especially with respect to their relation to meteorological circumstances. The two most important meteorological factors seem to be wind force and stability, greater wind force being connected with lower dust concentrations, greater stability with larger dust concentrations.

The influence of stability on the dust concentration is tested in two ways: firstly by relating dust content to wind direction, the latter being a qualitative indication for the stability of the airmass flowing over the city; secondly by analyzing the diurnal variation of the dust content.

The investigations with respect to the influence of wind force and wind direction on the dust content are restricted to the observations made in Rotterdam. All observations are tested however with respect to the diurnal variation of dust content. Apart from a single discrepancy with respect to the observations made in The Hague in the month of June, 1961, all observations confirm the general result, notably that, at least in the flat western part of the Netherlands, atmospheric stability is a meteorological factor of primary importance in determining the dust content in cities. Similar results were found for the city of Montreal by P. W. SUMMERS (1962).

Although dust, due to the influence of its deposition velocity on the daily course of the dust content e.g., may behave a little at variance with gaseous pollutants, the dimensions of the measured dust particles were so small ($< 5\mu$) that it seems quite safe to assume that the results found for the dust content will also hold for pollutants such as SO_2.

1. THE MEASUREMENTS MADE IN ROTTERDAM

The city of Rotterdam is situated in the very flat western part of the Netherlands at a distance of about 25 km from the North Sea. The city as well as its surroundings are intensively industrialized so that the air is more contaminated that in most other regions of the country. Apart from industry and domestic heating shipping should be mentioned as a source of pollution, Rotterdam being the second largest harbour of the world in 1957 and 1958.

Since 1957 the dust content of the air in Rotterdam has been determined at the Food Inspection Department, situated at about 300 m to the north of the river Meuse and the most important harbours and at almost the same distance to the NNW of a power station being the largest industry in the immediate neighborhood.

Figure 1 shows the situation of the observation point and the most important industrial sources of pollution in the surroundings. The maximum amounts of fuel used per hour by the various plants are given in the legend to the figure.

The measurement of the dust content of the air was made with an A.I.S.I. Smoke Recorder, placed at a height of 4,5 m above street level. Air is sucked upward to a volume of some 7 liters per minute and is forced to pass a Whatman No. 4 filterband which automatically moves discontinuously over a certain distance every hour (every two hours during the summer months). The diameter of the dust stains that are supposed to originate from particles smaller than 5μ only, amounts to about 1 inch.

Unfortunately it was not possible to measure the transmissivity of the stains with sufficient accuracy. Consequently information on the dust content of the air had to be deduced from reflectivity measurements. These were made with an E.E.L. reflectometer without application of filters.

It should be appreciated that in applying this method, black particles will contribute relatively more to the total result than grey ones, whereas white particles will contribute hardly at all. This means that the resulting values are related more closely to the quantity of soot present in the atmosphere than to its total dust content.

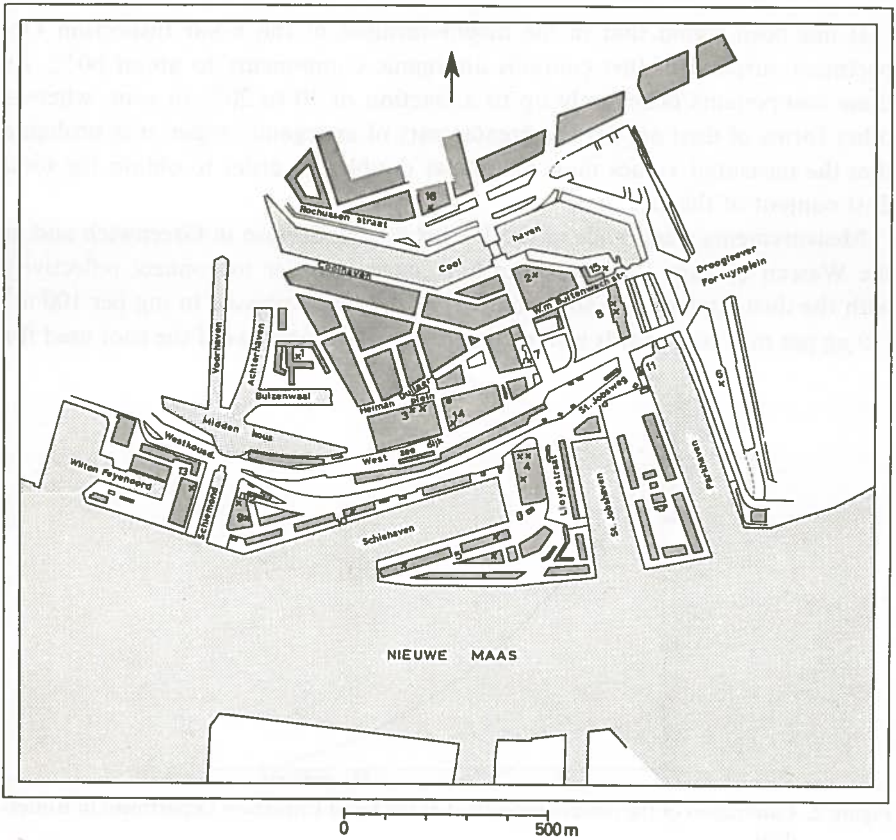

Figure 1. Centre of Rotterdam. Scale 1 : 18.500.
Dark areas denote buildings, grey areas like the one in the south, containing the name *Nieuwe Maas*, indicate water surfaces.
The observation point lying in the centre of the map is indicated by a dot.
The numbered crosses refer to the most important pollution sources, only those using coal (c) as a fuel, being of importance for the present investigation, oil (o) not leading to contamination of the atmosphere by soot.

Nr.	1	2	3		4	5	6	7	8	
FUEL	o	o	c	o	c	c	o	c	c	o
Max. use in kg/h	500	45	40	50	13500	60	60	60	300	200

Nr.	9	10	11	12	13	14	15		16
FUEL	o	o	c	c	o	o	c	o	o
Max. use in kg/h	47	58	80	45	400	40	70	200	20

It has been found that in the neighbourhood of the Food Inspection Department suspended dust contains anorganic components to about 60%. As these components occur only up to a fraction of 10 to 20% in soot, whereas other forms of dust are for the greater part of anorganic origin, it is probable that the measured values must be almost doubled in order to obtain the total dust content of the air.

Measurements were made at the Fuel Research Station in Greenwich and at the Warren Springs Laboratory in Stevenage in order to connect reflectivity with the dust content (i.e. soot content) of the air, expressed in mg per 100 m^3 (10 μg per m^3) as a unit. It is improbable that the blackness of the soot used for these check measurements will be the same as that of the soot collected in Rotterdam. For these reasons the exact factor with which the results should be multiplied in order to get the real *dust* content of the air is not known so that no such factor has been introduced. It is assumed, however, that the contamination of the air by particulate matter is given by the measurements to at least the correct order of magnitude.

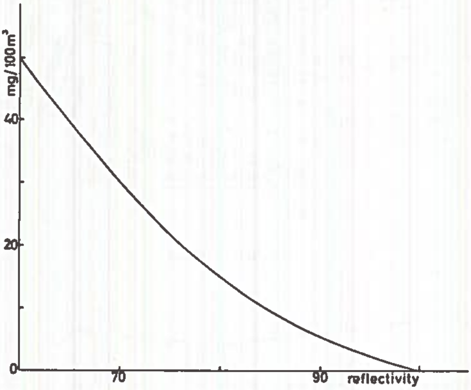

Figure 2. Calibration of the reflectometer used at the Food Inspection Department in Rotterdam.

The calibration of the reflectometer that was performed in the Warren Springs Laboratory is represented in figure 2.

In the following we will neglect the uncertainties mentioned above and relate the results of the reflectivity measurements with the 'dust content' of the air. In doing so we base ourselves on the observations made during the years 1957 and 1958.

Similar measurements, but only for a period of about one year, are available for three observation points, two in The Hague at about 3 km from the coast and one in Delft, some 11 km inland. Due to the shortness of the series the analysis of these observations has been much more limited. In fact only the diurnal variation of the dust content in these two cities has been considered and compared with the results pertaining to Rotterdam.

2. THE ANNUAL VARIATION OF THE DUST CONTENT OF THE AIR IN ROTTERDAM

As already stated above the dust content of the air was determined every hour during the winter months (October through March), whereas during the rest of the year two-hourly observations were obtained. Some observations lacking, due to various causes, the best way to proceed in order to get the monthly values of the dust content seemed to be to determine hourly values for the various months first and consequently to derive the monthly value from the 24 or 12 values thus obtained.

Table 1 gives the results of this procedure for the two years that have been investigated.

Table 1. Monthly mean value of dust content in Rotterdam in mg/100 m^3

	J	F	M	A	M	J	J	A	S	O	N	D	year
1957	9,3	10,3	9,3	4,3	3,8	3,4	3,3	3,5	3,8	8,9	5,8	8,6	6,2
1958	8,2	5,5	5,6	3,9	3,5	3,1	2,8	3,7	3,9	3,6	7,3	7,4	4,9

Although the general trend of both series is the same, large values during the winter months as compared with the summer values, there appear to occur some striking differences between the two years that have been considered. This holds especially for the months of February, March and October when contamination was about twice as high in 1957 as it was in 1958.

An attempt was made to find out whether meteorological factors could be held responsible for these differences.

Firstly, the inhomogeneity of the source distribution has been taken into account. The distribution of industries indicated in figure 1 suggests that wind directions from SW through S to NE will tend to supply more soot than those from SW through N to NE.

Secondly, high wind speeds will generally result in stronger turbulence than low wind speeds. As a consequence more dust will be diffused to higher levels during high wind speeds than during low wind speeds so that in the former case smaller concentrations will be detected by the Smoke Recorder.

Finally, precipitation may have a tendency to diminish the dust content of the air as a consequence of wash-out, the effect depending strongly on the dimensions of the dust particles, however.

It is true that during the heating season other meteorological factors such as temperature, might be of additional, perhaps even of primary importance. However, March 1958 having been much colder than March 1957 (−0,6 °C against +5,0 °C for the Netherlands as a whole) the temperature influence does not seem to be the most important one. Moreover, it did not seem reasonable to introduce more variables into the discussion, the number of monthly mean values being too small for any further differentiation.

In order to find a numerical relation between the three meteorological factors mentioned above and the dust content of the air, the total percentages of wind directions between SW and NE through S, the average wind speeds and the amounts of precipitation have been determined for each month of both years. Wind direction and wind speed data were taken from the central station De Bilt, some 50 km NE of Rotterdam and assumed to be sufficiently representative for the area under consideration, at least for the present investigation. Precipitation data refer to Naaldwijk, about 20 km NW of Rotterdam.

For the four quantities: wind direction percentage, wind speed, precipitation and dust content, the ratios for the years 1957 and 1958 have been determined for each month. They are given in table 2.

Table 2. Ratio of percentage of wind directions from SW through S to NE (d), average wind speeds (f), amount of precipitation (R), observed dust contents (D) and computed ratio of dust contents (D^*). In all cases the values of 1957 are divided by those of 1958

	d	f	R	D	D^*
Jan	0,94	1,03	0,33	1,13	1,22
Feb	1,27	0,86	0,93	1,87	1,92
Mar	1,37	1,30	1,64	1,66	1,71
Apr	0,87	0,68	0,43	1,10	1,39
May	0,59	0,94	1,26	1,08	0,66
Jun	0,83	0,93	0,39	1,10	1,11
Jul	0,93	0,82	1,72	1,18	1,36
Aug	0,86	1,20	1,74	0,95	0,91
Sep	0,88	0,96	2,02	0,97	1,14
Oct	1,31	0,83	0,74	2,47	2,02
Nov	1,12	1,86	1,14	0,79	0,81
Dec	1,02	1,11	0,51	1,16	1,28
Mean values and standard deviation	1,00 ± 0,22	1,04 ± 0,30	1,07 ± 0,58	1,29 ± 0,46	1,29 ± 0,21

From the 12 values of d, f, R and D it is possible to deduce the following linear regression equation by the method of least squares:

$$D^* = +\,1{,}74d - 0{,}85f - 0{,}02R + 0{,}46\,. \qquad (1)$$

The relation can be interpreted qualitatively as an indication that the dust content of the air near the ground increases when wind directions are 'favourable' and decreases with increasing wind speed, whereas the amount of precipitation seems to be of little importance. The correlation between D and D^* amounts to 0.90, 0.86 being the 1 % confidence limit (BROOKS and CARRUTHERS (1953), appendix IX). It is not so, of course, that in case d, f and R would have been unity, i.e. meteorological circumstances identical in both years, the average dust amount in 1957 would have been 1,33 times that in 1958; relation (1) has, of course, not a physical significance.

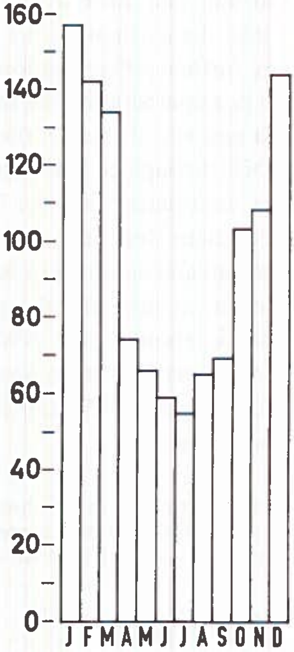

Figure 3. Monthly mean values of dust content of the air in Rotterdam, averaged over the years 1957 and 1958 and expressed as percentages of the average value, 5.55 mg per 100 m³.

The influence of the wind on the dust content will be considered in more detail in sections 6 and 7.

Figure 3 shows the distribution of dust content over the year, averaged over 1957 and 1958 and expressed as a percentage of the average value, 5.55 mg per 100 m^3. In spite of the fact that wind speed is larger during the winter than during the summer season, winter concentrations are about twice as high as those in summer.[1] This will be due for the greater part to the larger soot production during the cold season, notably from domestic chimneys. The large decrease of the dust content from March to April as well as the increase from September to October may be considered to confirm this assumption.

However, the difference in dust content between the hot and the cold seasons may partly be caused by differences in atmospheric stability. We will come back to this point in detail later on.

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[1] See also table 8, however.

3. THE RELATION BETWEEN THE DUST CONTENT IN ROTTERDAM AND THE DAY OF THE WEEK

It is to be expected that the concentration of air pollution will show differences in dependence of the day of the week. In most places where the behaviour of pollution through the week has been investigated the Sunday concentrations have been found to be smaller than those on week days.

Similar results are found with respect to the dust content of the air in Rotterdam. Table 3 gives these results for the 'summer' months April–September as well as for the months of the heating season October–March, averaged over the two years. Holidays such as Christmas and New Year have been excluded from the computation.

Table 3. Mean dust content in mg per 100 m³ in dependence of the day of the week

	Su	Mo	Tu	We	Th	Fr	Sa
April-September	2,0	3,6	4,0	3,9	4,1	3,8	3,7
October-March	4,8	8,5	8,7	8,8	8,7	7,2	6,6

Figure 4 shows the weekly variation for both seasons, summer and winter, expressed as percentage of the average values, respectively 3,6 and 7,5 mg per 100 m^3. In both seasons the Sunday dust content is only about half that on Tuesday through Thursday. Besides, there is a difference between the summer and the winter season as far as the behaviour of dust content towards the weekend is concerned. The fact that the contamination of the air decreases much stronger in winter than in summer after Thursday may be caused by the lowering of industrial capacity as well as of heating capacity on Friday afternoons. The fact that the dust content of the air is so greatly reduced on Sundays is, apart from the above-mentioned effect of industrial and heating capacity, most probably due to the much lower intensity of traffic during the weekend.

Meteorological influences can, of course, not play a role in the observed behaviour of the dust content during the week.

From figure 4 it can finally be deduced that the three days Tuesday, Wednesday and Thursday can be considered almost equivalent with respect to atmospheric contamination.

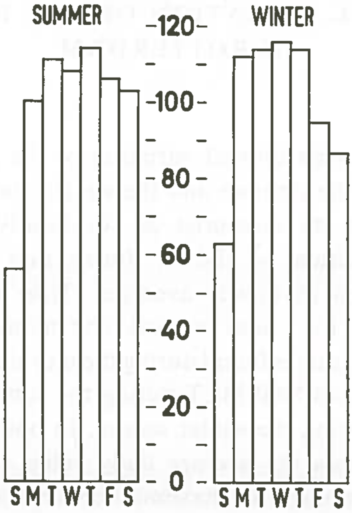

Figure 4. Weekly variation of the dust content of the air in Rotterdam for the summer- and winterseason, given as percentages of the average values, 3.6 and 7.5 mg per 100 m^3.

4. THE DIURNAL VARIATION OF THE DUST CONTENT IN ROTTERDAM

Figure 5 shows the mean diurnal variation of the dust content of the air in Rotterdam for both the summer and the winter season. As we said before, summer concentrations are measured as two-hourly averages, due to the relatively small dust content of the air during that season whereas winter concentrations are given as hourly averages. Time indications are in Mid European Time, i.e. GMT + 1 hour or local time minus 20 minutes.

A maximum concentration is found during the morning hours in both seasons. It occurs between 6.00 and 8.00 MET during the summer period and between 8.00 and 10.00 MET during the winter season. In both seasons the maximum amounts to about $\frac{3}{2}$ times the average daily value during that season. The difference between the moment of maximum concentration in the two seasons may be connected with a shift in the moment of sunrise and, therefore, with the

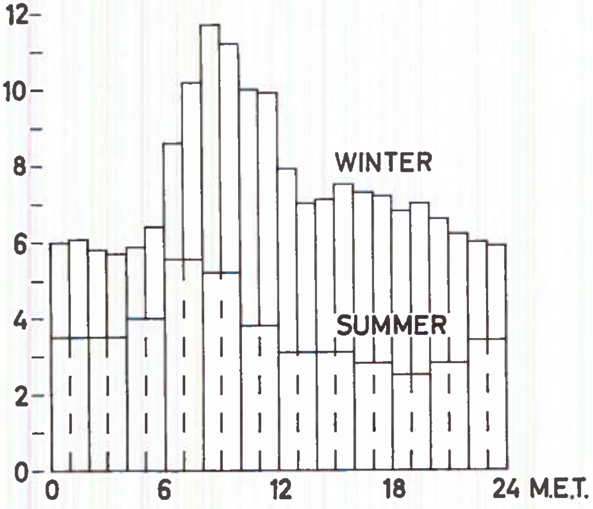

Figure 5. Diurnal variation of the dust content of the air in Rotterdam expressed in mg per 100 m³ for the summer and the winter season.

moment of maximum stability of the atmosphere. This consequence of atmospheric stability will later be considered in detail.

There exists a striking diurnal variation in the ratio between winter and summer concentrations, D_w/D_s. In figure 6 this value is plotted for every hour,

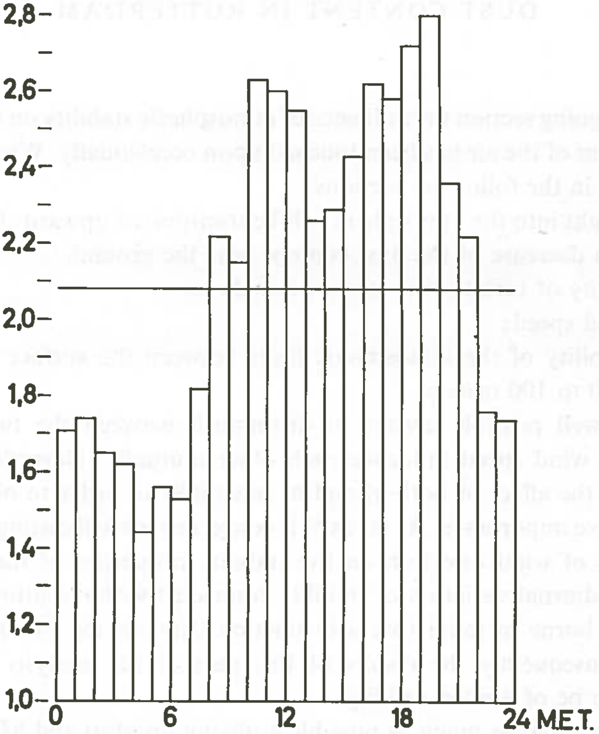

Figure 6. Diurnal variation of the ratio D_w/D_s between winter values, D_w, and summer values, D_s, of the dust content of the air in Rotterdam. The horizontal line at $D_w/D_s = 2.08$ gives the average ratio between the winter and the summer values of the dust content, irrespective of the time of the day. Obviously this value 2.08 equals 7.5/3.6 (see legend fig. 4).

the horizontal line at $D_w/D_s = 2{,}08$ giving the average for the whole day. The high values of D_w/D_s between 8 and 22 h are probably due to domestic heating during this part of the day. This might also explain the fact that the graph shows maxima during the morning hours as well as in the late afternoon and early evening. On the other hand, the different diurnal variation of stability during the winter and the summer seasons may also contribute to the phenomenon.

5. THE INFLUENCE OF ATMOSPHERIC TURBULENCE ON THE DUST CONTENT IN ROTTERDAM

In the foregoing section the influence of atmospheric stability on the variations in dust content of the air has been touched upon occasionally. We will look into this problem in the following sections.

Dust brought into the atmosphere will be transported upwards by turbulence resulting in a decrease of the dust content near the ground.

The intensity of turbulent motions depends on

a) the wind speed;

b) the stability of the atmospheric layer between the surface and, say, an altitude of 50 to 100 meters.

It is not well possible always to distinguish between the two factors as stability and wind speed influence each other mutually. Nevertheless we will try to detect the effect of both *a*) and *b*) separately in order to obtain an idea of their relative importance. As far as *b*) is concerned we will distinguish between the influence of wind direction on the stability properties of the atmosphere (*b1*) and the diurnal variation of stability connected with radiation (*b2*). Again it should be borne in mind that a distinction between the two is not always possible. Consequently the results of this part of the analysis can only be considered to be of limited validity.

In order to avoid as much as possible a mixing up of *a*) and *b1*) with *b2*) we restrict the investigation with respect to the first two effects to the period between 13 and 18 hours MET during which period no substantial influence of the diurnal variation is to be expected. (See figure 5).

Furthermore, in order to make the investigation as representative as possible we also confine it to Tuesdays, Wednesdays and Thuersdays. For a study of the diurnal variation of the dust content the complete material will be taken into account.

6. THE INFLUENCE OF WIND FORCE ON THE DUST CONTENT IN ROTTERDAM

Increasing wind speed will lead to an increase of dynamic turbulence in the lower layers. This will especially be so above the rough terrain formed by a city. Consequently it may be expected that under circumstances with high wind speeds the dust content measurements will reveal lower values than during situations with low wind speeds.

Figure 7 shows the relation between the dust content *D* in mg per 100 m^3 and the wind force measured at the airport of Rotterdam. Further refinements not seeming to be of significance, the Beaufort-scale has been used to characterize the wind speed, 6 Bft being the largest value that could be taken into account. The number of observations in each class is indicated in the figure.

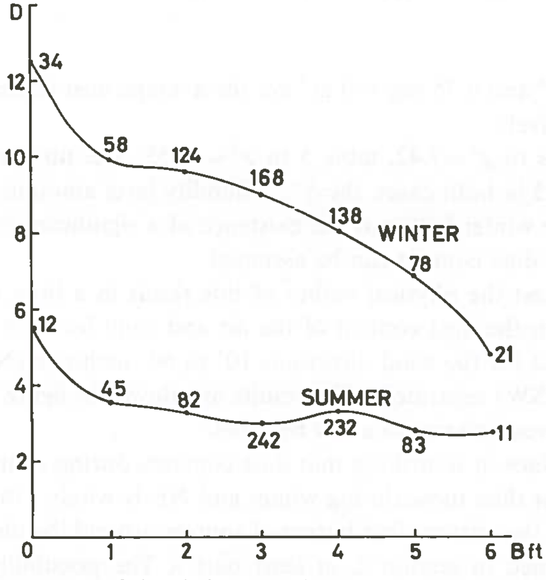

Figure 7. Dust content, *D*, of the air in Rotterdam, in mg per 100 m^3 against wind force measured at the airport of Rotterdam for the winter and the summer season. The numbers of observations for each wind class are inserted in the figure.

A striking difference can be observed between the winter and the summer curves. Whereas in both seasons the dust content shows a maximum value for calm, from 1 Bft upwards there is a gradual decrease in dust content with increasing wind force during the winter season but during the summer season the influence of wind force on the dust content seems to be only small.

This difference in behaviour has been tested by the χ^2-method based on the contingency tables 4 and 5:

Table 4. Contingency table for the summer half year

	1	2	3	4	5	6Bft	
> 3,19	25	37	106	99	27	4	298
< 3,19	20	45	176	133	56	7	437
	45	82	282	232	83	11	735

Table 5. Contingency table for the winter half year

	1	2	3	4	5	6Bft	
> 8,75	31	56	76	59	21	5	248
< 8,75	27	68	92	79	57	16	339
	58	124	168	138	78	21	587

3.19 mg/100 m^3 and 8.75 mg/100 m^3 are the average dust contents for the two periods respectively.

Table 4 leads to $\chi^2 = 7.42$, table 5 to $\chi^2 = 12.55$. The number of degrees of freedom being 5 in both cases, the 5 % reliability level amounts to 11,1 so that only during the winter half year the existence of a significant relation between wind force and dust content can be assumed.

In order to test the physical reality of this result in a little more detail the relation between the dust content of the air and wind force ($\geqslant$ 1 Bft) has also been determined for the wind directions 10° to 60° inclusive (NE) and 190° to 240° inclusive (SW) separately. The results are shown in figure 8.

The four curves give rise to a few remarks.

In the first place, it is striking that dust contents during summer and SW-ly winds are higher than those during winter and NE-ly winds. Obviously this is a consequence of the uneven distribution of sources around the observation point already mentioned in section 2, at least partly. The possibility that stability differences also play a part should, however, not be excluded.

Secondly, the curves behave less regularly than those reduced from all observations as represented in fig. 7, probably due to the smaller number of observations that have been used.

We, therefore, added the observations pertaining to 1,2 and 3 Bft on the one hand and those pertaining to 4,5 and 6 Bft on the other. Table 6 shows the results.

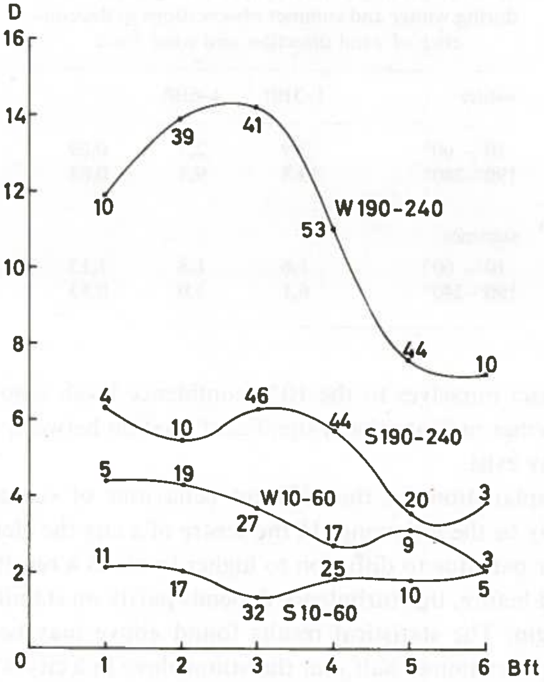

Figure 8. Dust content of the air in Rotterdam in mg per 100 m³, *D*, against wind force, measured at the airport of Rotterdam for the winter and the summer season and for wind directions 10° to 60°, inclusive and 190° to 240°, inclusive, respectively. The numbers of observations for each wind class are inserted in the figure.

The figures in the last column give the ratio of the dust content during wind forces 4–6 Bft and the one during wind forces 1–3 Bft. Again it is seen that the influence of wind force is stronger during the winter half year than it is during the summer half year.

The result has again been tested statistically along the same lines as before, now with the aid of the four tetrachoric schemes given in table 7.

The values of $\bar{D}$, the average dust content for the four cases, amount to 1.7, 5.5, 3.5 and 11.3 mg per 100 m^3 respectively. The corresponding χ^2-values are

2.30, 0.30, 3.08 and 16.64 respectively. The 5% reliability level equals 3.84 for 1 degree of freedom, so that a significant relation between wind force and dust content only seems to exist in the case of SW-ly winds during the winter half-year. If we restrict ourselves to the 10% confidence level, amounting to 2.71, both winter schemes indicate that a significant relation between wind force and dust content may exist.

Table 6. Average dust content in mg per 100 m^3 during winter and summer observations in dependence of wind direction and wind force

winter	1–3Bft	4–6Bft	
10°– 60°	3,9	2,7	0,69
190°–240°	13,8	9,3	0,68
summer			
10°– 60°	1,6	1,8	1,13
190°–240°	6,1	5,0	0,83

A possible explanation for the different behaviour of summer and winter observations may be the following: In the centre of a city the cleaning of the air is for the greater part due to diffusion to higher levels as a result of turbulence. As has been said before, this turbulence depends partly on stability and is partly of dynamic origin. The statistical results found above may be interpreted as follows: During the summer half year the atmosphere in a city is generally more or less unstable, at least during the period of the day that has been used for this investigation. Differences in wind speed, resulting in a different dynamic component of the turbulent motions will add little to the total diffusion, as

Table 7. Tetrachoric schemes to test the relation between wind force and dust content

Summer								Winter							
10°–60°				190°–240°				10°–60°				190°–240°			
	1–3 Bft	4–6 Bft			1–3 Bft	4–6 Bft			1–3 Bft	4–6 Bft			1–3 Bft	4–6 Bft	
$>\bar{D}$	23	22	45	$>\bar{D}$	25	24	49	$>\bar{D}$	22	6	28	$>\bar{D}$	53	31	84
$<\bar{D}$	38	18	56	$<\bar{D}$	35	44	79	$<\bar{D}$	29	23	52	$<\bar{D}$	37	76	113
	61	40	101		60	68	128		51	29	80		90	107	197

increasing wind speed will as a rule lead to a decrease of thermal convection so that the total upward transport of pollution will remain almost constant.

During the winter season, however, the lower layers of the atmosphere tend to be in stable equilibrium, even in the centre of a city and under these circumstances turbulence will for the greater part be of dynamic origin and will strongly depend on wind force, therefore.

Total or almost total lack of wind may in both seasons be due to anticyclonic conditions with relatively large stability of the layers near the surface. Such circumstances are more common during winter than they are during summer. This fact is reflected in the number of cases with wind force 0 in this investigation, notably 5,5 % in the winter half-year against 1,6 % in the summer half-year. A typical example of such a situation occurred during the first days of December 1962, when the dust content in Rotterdam rose to a 24 hours' value of 53 mg/100 m^3 during an anticyclonic circulation over the Netherlands with ground inversions showing a temperature increase between the ground and 100 m of some 10 °C. The highest daily value of the dust content in the years 1957 and 1958 was 25 mg/100 m^3.

7. THE INFLUENCE OF WIND DIRECTION ON THE DUST CONTENT IN ROTTERDAM

Discussing the annual variation of the dust content of the air in Rotterdam we found that wind direction shows a certain influence in this matter. This appeared from the comparison of the two observation years used in this survey (cf. para 2). The influence of the wind direction was then described to the uneven distribution of the dust sources. On the other hand wind direction must have an indirect influence on the dust content of the air as winds from different directions may advect air of different stability.

In order to study this effect we have again restricted ourselves to the use of the observations of Tuesdays, Wednesdays and Thursdays and the values of the dust content between 13 and 18 MET. The relevant observations were again divided into those made during the winter half year and those made during the summer half year.

Figure 9 shows the average dust content as a function of wind direction and for both seasons (curves I and II). In order to avoid as much as possible irregularities due to the distribution of sources the values for 20°, 30° and 40° wind direction have been averaged and inserted at 30°; likewise those for 50°, 60° and 70°, the average value being inserted at 60°, etc. Figures along curves I and II indicate the number of observations, from which it appears that during the summer season (II) the winds blow mostly from directions between N and W, whereas in the winter half year (I) SSW-ly winds are predominant.

There are two directions which show an excess dust content, namely East and SSW. Not taking into consideration cases with variable winds, mostly connected with wind force $\leqslant 1$ Bft, the various wind directions show the following average wind force:

Table 8. Average wind force in the Beaufort-scale as a function of wind direction given in tens of degrees

wind direction	36	3	6	9	12	15	18	21	24	27	30	33
winter	2,8	3,0	3,4	2,4	2,6	2,6	3,3	3,6	3,6	3,4	3,6	3,3
summer	3,6	3,4	3,0	3,3	3,3	2,7	3,4	3,1	3,8	3,2	3,2	3,4

The fact that the mean wind speed is slightly higher during the summer half year than during the winter half year, 3,3 against 3,1 Bft, is due to periods with calms or weak winds during October and November 1958.

Table 8 shows that the high concentrations during E-ly winds in winter may

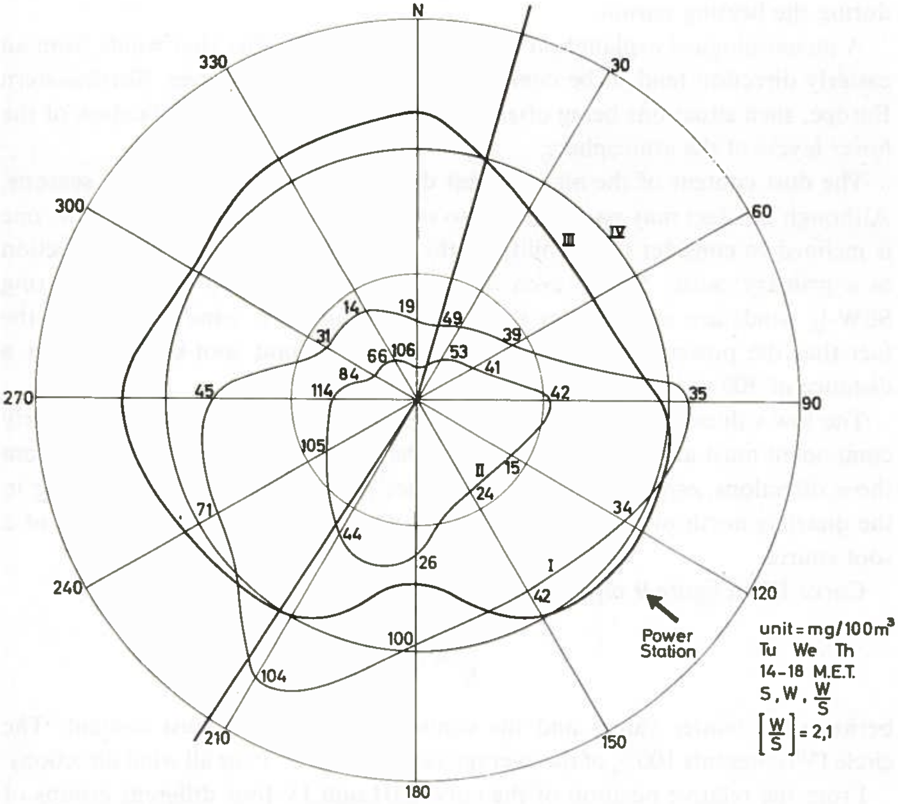

Figure 9. Dust content for the winter (*I*) and the summer (*II*) season in Rotterdam in relation to wind direction. The circles represent 5, 10 and 15 mg per 100 m³, respectively. Curve *III* represents the ratio between the winter dust content *W* (given by curve *I*) and the summer dust content *S* (given by curve *II*) as a percentage of the average value of this ratio, amounting to 2.1. The deviation from 100% can be determined from the course of curve *III* with respect to the three circles mentioned before, the inner circle now corresponding with 50%, the second circle (*IV*) with 100% and the outer one with 150%.
All values have been determined for every 30°, the numbers along curves *I* and *II* indicating the number of observations used.
The thick lines at 16° and 213° correspond with the wind directions at which a transition takes place between values of $W/S > 100\%$ and $< 100\%$, respectively.

partly be connected with the fact that the wind force was relatively small during winds from that direction.

As to the high summer values during E-ly winds the only plausible explanation could be that it is due to pollution from sources east of the observation post that may be of greater relative importance during the summer season than during the heating season.

A meteorological explanation could be found in the fact that winds from an easterly direction tend to be connected with high pressure over Northwestern Europe, such situations being often characterized by stable stratification of the lower layers of the atmosphere.

The dust content of the air is largest during SSW-ly winds in both seasons. Although this fact may partly be due to soot originating from the harbours one is inclined to consider the stability of the atmosphere with this wind direction as a primary cause. This is even more obvious as the concentrations during SSW-ly winds are much larger than those during SE-ly winds in spite of the fact that the power station, by far the most important soot-source, lies at a distance of 300 m in SE-ly direction.

The low values of the dust content of the air during winds with a northerly component must at least partly be due to the instability of the air arriving from those directions, especially during the winter season when domestic heating in the quarters north of the observation post will by no means be negligible as a soot source.

Curve III in figure 9 represents the ratio

$$\frac{W}{S} = P$$

between the winter values and the summer values of the dust content. The circle IV represents 100 % of the average value $\bar{P} = 2{,}1$ of P for all wind directions.

From the relative position of the curves III and IV four different groups of wind directions can be distinguished:

a) Between 16° and 95° P is smaller than the average value, the minimum amounting to 80 % of that value.

b) Between 95° and 150° P is slightly larger than $\bar{P}$, the excess being at most 4 %, however.

c) For wind directions between 150° and 213° P is again smaller than $\bar{P}$, the minimum value now being 74 %.

d) For all wind directions between 213° and 16°, finally, $P > \bar{P}$ the maximum excess amounting to 17 % for westerly winds.

If we ascribe the small maximum of P in the second sector to the fact that during the heating season the soot production by the power station SE of the observation point will be much larger than during the summer half year, we may state that due to geographic circumstances $P > \bar{P}$ for wind directions in the westerly sector between 213° and 16° and $P < \bar{P}$ for wind directions in the easterly sector between 16° and 213°.

Figure 10 shows the two sectors on a map of the Netherlands. It appears that the boundaries mentioned under *d*) notably from Rotterdam in the

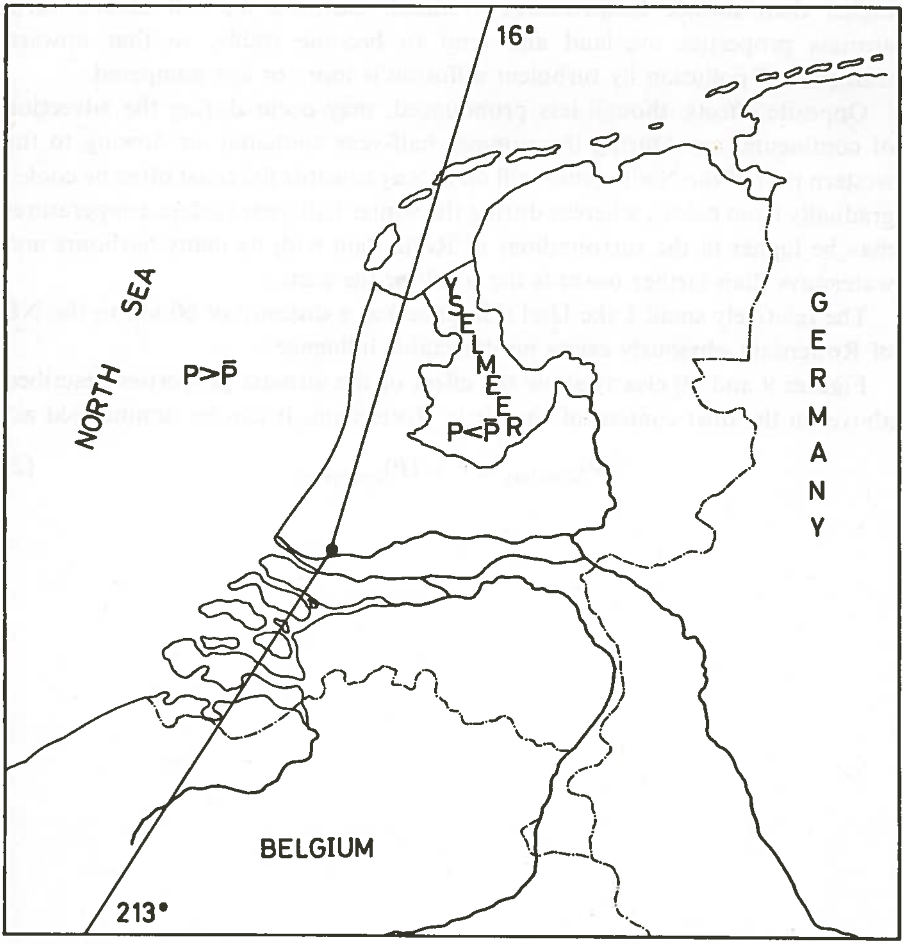

Figure 10. Position of the 16° and 213° lines of figure 9 on a map of the Netherlands.

directions 16° and 213° almost coincide with the transition between onshore and offshore winds. The reason for the opposite behaviour of $P/\bar{P}$ during winds from the easterly sector and from the westerly sector can now be understood at least qualitatively. During the warm season sea water will show in the average lower temperatures than a land surface and notably so during the afternoon. The maritime air advected from the sea will obtain cold airmass properties overland and will tend to become unstable. Pollution will be easily diffused upwards under these circumstances and the dust content of the air will be relatively small. During the cold season seawater temperatures will be higher than surface temperatures overland, maritime air will obtain warm airmass properties overland and tend to become stable, so that upward transport of pollution by turbulent diffusion is more or less hampered.

Opposite effects, though less pronounced, may occur during the advection of continental air. During the summer half-year contental air flowing to the western part of the Netherlands will on its way towards the coast often be cooled gradually from below, whereas during the winter half-year surface temperatures may be higher in the surroundings of Rotterdam with its many harbours and waterways than farther towards the south or the east.

The relatively small Lake IJsel (IJselmeer) at a distance of 60 km to the NE of Rotterdam obviously exerts no detectable influence.

Figures 9 and 10 clearly show the effect of the airmass properties described above on the dust content of the air in Rotterdam. It can be summarized as:

$$(P)_{\text{maritime}} > \bar{P} > (P)_{\text{continental}} \, . \tag{2}$$

8. THE INFLUENCE OF STABILITY AS SHOWN BY THE DIURNAL VARIATION OF THE DUST CONTENT IN ROTTERDAM

In order to get a better insight into the influence of atmospheric stability on the contamination of the air in Rotterdam, an influence already discussed in the foregoing section, the daily variation of the dust content has been considered in more detail than in section 4. No distinction has now been made between the

Table 9. Two-hourly dust content averaged for the 24 months of 1957 and 1958 in percentages of the monthly mean value. The first column under each time indication, given in MET, refers to 1957, the second one to 1958

	0–2		2–4		4–6		6–8		8–10		10–12	
J	76	72	73	78	75	80	125	105	152	152	145	151
F	80	88	67	82	72	77	113	112	170	141	154	125
M	89	88	100	77	106	89	128	163	139	140	100	100
A	80	92	77	92	110	97	143	154	177	159	138	113
M	113	123	105	123	116	151	150	140	121	106	87	94
J	124	107	115	110	159	117	168	160	126	160	97	110
J	121	100	91	96	115	132	200	175	130	157	100	118
A	94	86	83	103	83	92	149	135	143	146	111	97
S	92	72	92	95	103	100	166	165	139	168	105	110
O	79	89	76	67	84	67	137	131	161	128	131	133
N	67	67	66	77	83	101	134	144	170	184	133	133
D	81	99	76	73	70	76	98	113	139	141	146	131

	12–14		14–16		16–18		18–20		20–22		22–24	
J	99	117	107	99	111	105	90	85	74	80	73	77
F	104	95	90	105	92	111	111	98	86	80	66	79
M	82	89	84	91	83	81	97	88	108	88	81	96
A	93	82	88	79	74	72	66	82	71	79	92	85
M	68	94	87	86	82	83	82	60	79	89	95	66
J	65	90	59	83	50	63	56	53	76	77	118	80
J	73	75	73	68	76	64	79	54	64	71	91	93
A	100	97	123	100	86	95	69	76	83	95	120	76
S	87	90	92	88	92	88	76	72	82	75	89	70
O	94	111	89	97	91	125	85	108	86	81	85	78
N	105	93	109	82	102	93	90	85	76	75	66	73
D	108	100	122	92	104	81	86	87	83	100	86	100

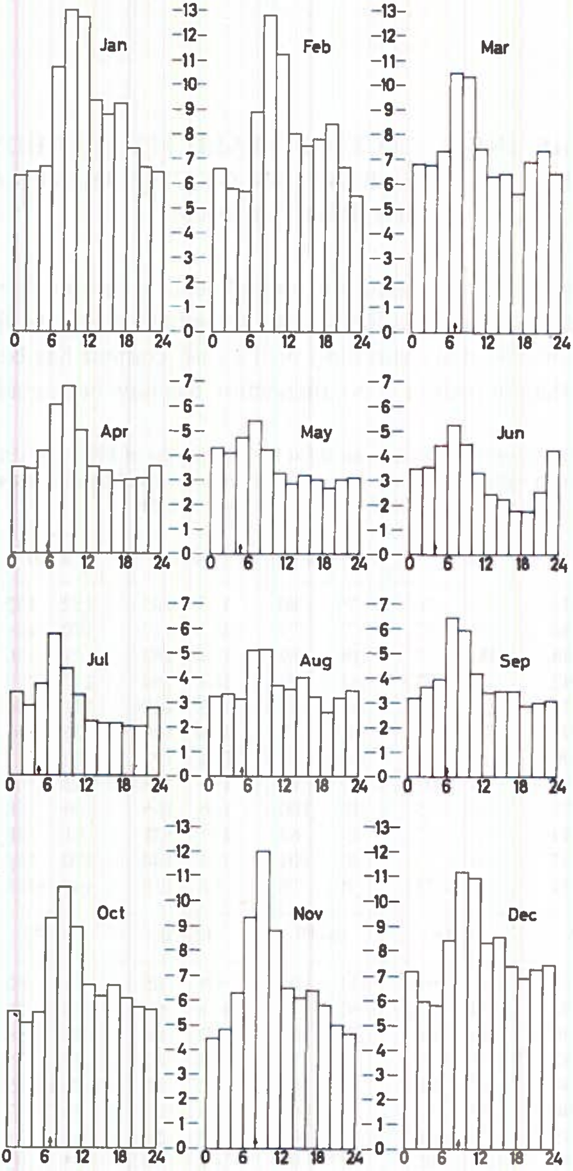

Figure 11. Two-hourly dust content of the air in Rotterdam in mg/100 cm³ for the twelve months of the year, averaged from the observations made in 1957 and 1958. The small arrow at the bottom of each histogram gives the time of sunrise for the 15th of the month.

days of the week but for every month of both years the average dust content for every two hours has been determined. See table 9, where the dust content is given as percentage of the mean monthly value.

Figure 11 shows the result as histogrammes giving the two-hourly dust contents as an average over both observation years. The 12 histogrammes all show a well-defined maximum during the morning hours and one less pronounced during the afternoon or early evening, especially those for the winter months.

The period during which the morning maximum is observed seems to shift a bit through the year. This can be seen more clearly in the following way. If we suppose the change in dust content near the maximum to be a continuous symmetric one and as a first approximation represent it by a parabola with vertical axis: $(x-x_0)^2=p(y_0-y)$, x being the horizontal coordinate (time) and y the vertical coordinate (dust content) we can determine x_0, the time at which the vertex of the parabola i.e. the maximum dust content occurs. As a matter of fact the parabola is completely determined by three points, namely the centre of the upper boundary of the column representing the maximum dust content and those of the columns immediately to the left and to the right. For January e.g. the parabola is determined by the three points (7; 10.7), (9; 13.0) and (11; 12.7). The first number represents the time median of each column, the second number the relative dust content. We so find three equations for every month to compute p, x_0 and y_0.

Table 10. Moment of maximum dust content t_m according to a parabolic approximation and moment of surnise t_s on the 15th of each month, both in MET

	t_m	t_s	$t_m - t_s$
January	9,9	8.7	1,2
February	9,4	8,0	1,4
March	8,3	6,9	1,4
April	8,6	5,7	2,9
May	6,8	4,8	2,0
June	7,0	4,3	2,7
July	7,2	4,6	2,6
August	8,0	5,3	2,7
September	7,7	6,2	1,5
October	8,9	7,1	1,8
November	8,9	7,9	1,0
December	9,8	8,7	1,1

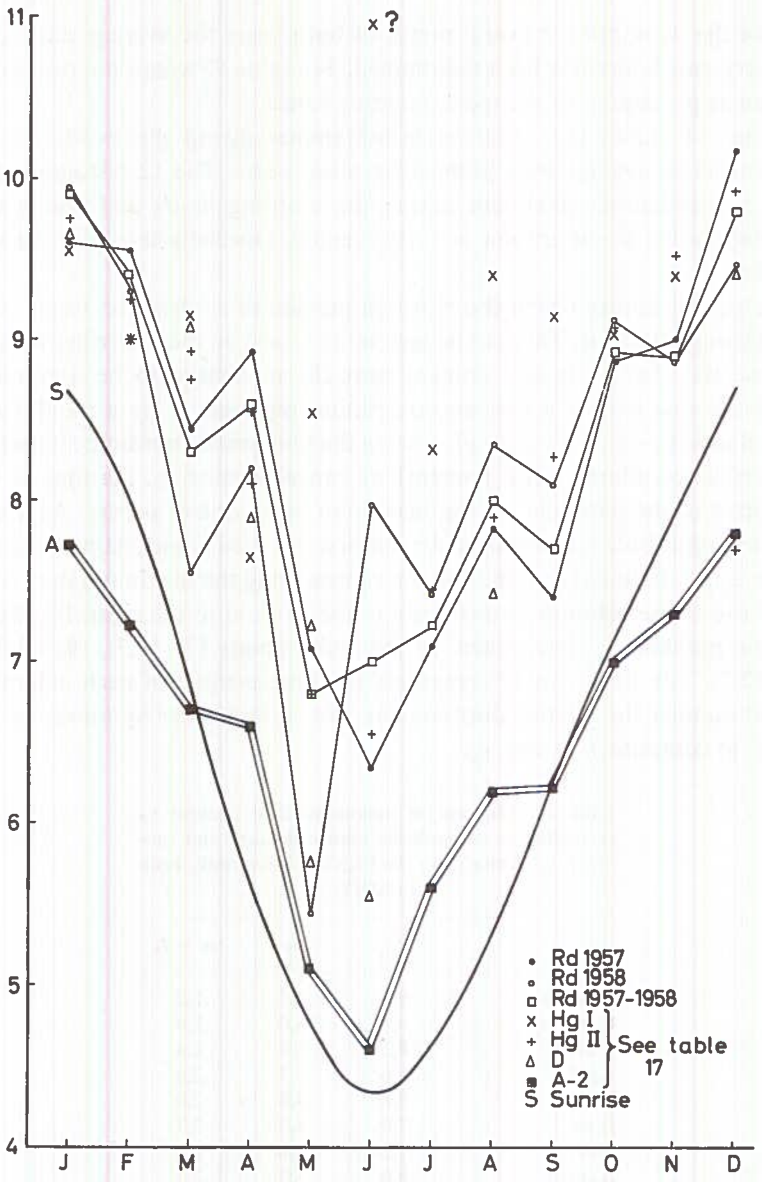

Figure 12. Moment of maximum dust content of the air in Rotterdam (Rd), The Hague (Hg) and Delft (D). *S* represents the moment of sunrise, whereas *A* gives the time of occurrence of the maximum, averaged from all observations, minus two hours. Time is in MET.
See also tables 17 and 18.

Table 10 gives the values of x_0 for the twelve months being a reasonable estimate of the moment of occurrence of the maximum dust content. In the second column the moment of sunrise on the 15th of the relative month is given. The third column gives the differences.

It follows from the table that the maximum dust content occurs between 1 and 3 hours after the moment of sunrise, the lag being largest during the summer months. The maximum difference in the time of sunrise amounts to 4,4 hours, that in the time of maximum dust content equals 3,1 hours. Figure 12 shows the yearly course of the time of occurrence of the maximum for both years as well as for the combination of the two. *S* represents the time of sunrise. Other points and *A* refer to table 18. The result points to a strong influence of atmospheric stability, the maximum dust content occurring too late during December and January and too early during May, June and July to be ascribed to anthropogenetic influences only. The variation of $t_m - t_s$ in the course of the year on the other hand makes it probable that such an influence cannot be totally ignored.

Table 11. Moment of maximum dust concentration t_m according to the parabolic approximation applied to observations made in Vienna. t_s gives the moment of sunrise. Both times are in MET

	t_m	1961	t_m	t_s	$t_m - t_s$
		J	9,3	7,7	1,6
		F	9,2	7,1	2,1
		M	7,7	6,2	1,5
		A	7,2	5,1	2,1
		M	7,0	4,3	2,7
		J	6,5	3,9	2,6
		J	6,4	4,1	2,3
		A	6,9	4,8	2,1
S 1960	8,6	S	7,1 (7,8)*	5,5	2,3
O	8,0	O	9,3 (8,6)*	6,2	2,4
N	8,6	N	9,3 (9,0)*	7,0	2,0
D	8,6	D	9,3 (9,0)*	7,6	1,4

* Average values over 1960 and 1961.

The same effect of an annual variation of the moment of occurrence of the morning maximum of concentration of pollution has been found elsewhere. SUMMERS (1962) observed it in Montreal, MUNN and KATZ (1959) in the Detroit-Windsor area.

Observations made by STEINHAUSER (1962) in Vienna where dust contents have been determined every three hours were subjected to the parabola method. The result is given in table 11.

In order to investigate this point further the diurnal variation of the dust content in Rotterdam has been analyzed harmonically for each month of both observation years.

9. HARMONIC ANALYSIS OF THE DIURNAL VARIATION IN DUST CONTENT

The diurnal variation of the dust content for the 24 months January 1957 to December 1958 has been analyzed harmonically up to the sixth harmonic, the first one representing the average value of the dust content, A_0 (BROOKS and CARRUTHERS, 1953). Table 12 gives the resulting values of the amplitudes $A_1 - A_5$ in percents of A_0 and the phase angles φ_1 to φ_5, φ being counted from 01.00 MET.

Table 12. Amplitudes and phase angles of the five harmonic components of the diurnal variation of dust content. Amplitudes are given as a percentage of the average value A_0 and φ is in degrees counted from 01.00 MET

	A_1	φ_1	A_2	φ_2	A_3	φ_3	A_4	φ_4	A_5	φ_5
Jan 1957	32,4%	298°	13,7%	215°	15,1%	89°	2,6%	273°	3,6%	36°
Feb	32,2	297	24,5	205	17,0	51	4,6	20	4,7	136
Mar	15,9	0	16,9	241	2,7	72	8,8	356	1,0	78
Apr	39,5	336	20,7	206	11,9	127	5,6	268	4,7	178
May	26,0	25	10,6	276	13,1	137	4,8	69	3,3	69
Jun	51,5	30	9,2	237	12,8	180	7,2	163	3,9	110
Jul	37,9	11	17,2	255	20,0	141	17,5	101	8,5	32
Aug	20,5	329	11,9	182	23,5	156	4,5	352	2,1	299
Sep	26,7	349	14,6	249	15,0	145	4,5	60	6,5	354
Oct	27,8	320	21,2	213	11,6	106	3,3	341	1,8	336
Nov	37,5	303	18,2	228	12,9	105	5,5	348	1,5	176
Dec	27,9	283	12,5	162	10,4	88	8,6	288	3,2	90
Jan 1958	32,7	296	14,3	185	10,3	58	7,9	264	2,2	298
Feb	20,7	293	9,4	220	14,8	84	2,6	332	1,0	66
Mar	21,3	343	19,6	231	15,9	153	8,9	61	3,2	338
Apr	31,0	350	19,3	224	12,0	116	7.1	31	0,9	291
May	32,7	19	12,9	350	4,5	236	3,3	65	10,2	50
Jun	42,4	0	9,5	215	11,3	137	8,9	11	2,9	16
Jul	46,9	4	17,4	229	13,4	148	2,3	160	3,3	43
Aug	20,8	335	9,7	249	9,3	129	12,2	354	6,1	323
Sep	37,5	337	19,7	248	13,0	126	8,4	2	6,6	312
Oct	25,1	280	12,7	223	13,8	89	9,5	117	7,5	358
Nov	38,3	325	24,8	229	12,5	93	4,2	308	4,2	234
Dec	15,4	313	21,6	181	7,8	107	2,6	7	3,2	88

The diurnal course of the dust content for each month is given by

$$D = A_0 + \sum_{k=1}^{k=5} A_k \sin\left[k\varphi + \varphi_k\right] \tag{3}$$

where 1 hour is equivalent with $\Delta\varphi = 15° = \pi/12$ radiant, $\varphi = 0$ for 01.00 MET.

In order to determine the relative importance of the five harmonics given in table 12 the values of

$$\frac{A_i^2}{\sum\limits_{k=1}^{k=5} A_k^2}$$

are given in table 13 in percentages.

Table 13. $\dfrac{A_i{}^2}{\sum\limits_{k=1}^{k=5} A_k{}^2} \times 100$

	1	2	3	4	5
Jan 1957	71%	13%	15%	0%	1%
Feb	53	30	15	1	1
Mar	40	47	1	12	0
Apr	71	20	7	1	1
May	67	12	18	2	1
Jun	89	3	5	2	1
Jul	57	12	16	12	3
Aug	38	12	48	2	0
Sep	59	17	18	2	4
Oct	56	33	10	1	0
Nov	73	17	9	1	0
Dec	69	14	10	6	1
Jan 1958	75	14	7	4	0
Feb	58	12	29	1	0
Mar	38	33	21	7	1
Apr	63	25	9	3	0
May	78	12	1	1	8
Jun	86	4	6	4	0
Jul	82	11	7	0	0
Aug	54	12	11	18	5
Sep	68	19	8	3	2
Oct	56	14	17	8	5
Nov	64	27	7	1	1
Dec	30	60	8	1	1
Mean	62	20	13	4	1

It is clear from this table that the first, the second and the third harmonics are by far the most important, contributing in the average for 95% to the diurnal variation. In order to get an impression of the influence of the time of the year on these three harmonics their phase angle φ_k is plotted against time, expressed as number of the month, in figure 13. Curve S gives the time of sunrise, expressed as a phase angle φ_s, again counted from 01.00 MET, being

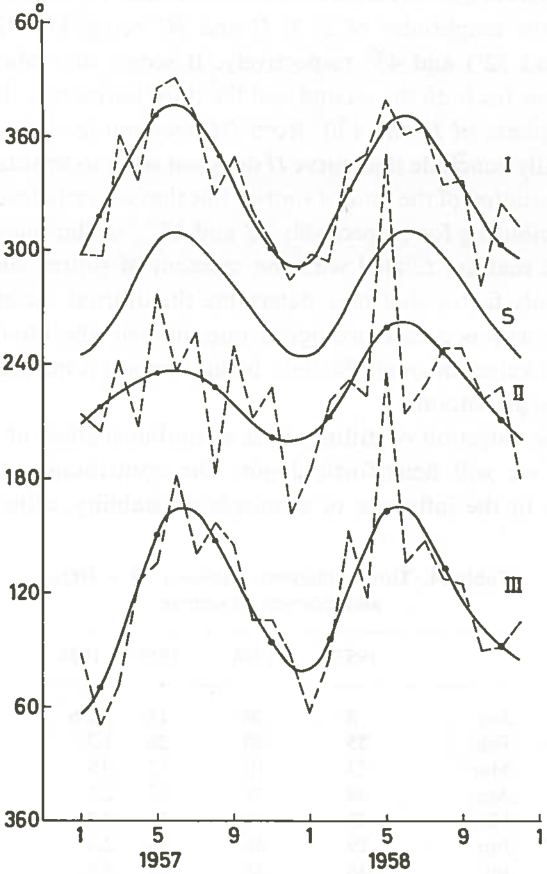

Figure 13. Phase angles for the first (*I*), second (*II*) and third (*III*) harmonics as well as for the moment of sunrise (*S*) expressed in degrees and counted from 01.00 MET. The dashed lines connect the phase angles found for every month. The smoothed curves *I*, *II* and *III* are drawn through the dots giving the average value of the phase angle for three successive months. Along the horizontal axis the months are given by their number: 1 = January, 5 = May, etc.

the centre of the first two-hourly period, 0000–0200 MET. The dashed lines belonging to the curves *I*, *II* and *III* indicate the real phase angle of the three harmonics for each year. It appears that φ_1 and φ_3 show a more regular course than φ_2. The curves *I*, *II* and *III* are drawn through the dots giving the average phase angle for three successive months. The curves *I* and *III* give the better approximation to the dashed lines, standard deviations being 15° and 22,8° respectively against 29,9° for curve *II*. There seems to be little difference between the degrees of parallelism between the curves *I*, *II* and *III* on the one hand and *S* on the other, the amplitudes of *S*, *I*, *II* and *III* being 34°, 42°, 25° (average between 18° and 32°) and 43° respectively. It seems that May 1958 shows a special behaviour for both the second and the third harmonics. Even subtracting 180° from the phase of *II* and 120° from *III* does not lead to more acceptable results. We finally conclude that curve *II* does not seem to be totally independent of the annual variation of the time of sunrise but that nevertheless it are especially *I* and *III*, contributing for respectively 62 and 13 % to the total daily variation in dust content that are related with the moment of sunrise and the length of the day. The only factor that may determine the diurnal variation of the dust content in this way is a meteorological one, namely the intensity of upward diffusion which varies through the day, being smallest a little after sunrise and large during the afternoon.

Although this variation of diffusivity is a combined effect of wind speed and static stability we will henceforth denote the contribution of *I* and *III* as principally due to the influence of atmospheric stability, although, of course,

Table 14. Time difference between $(I + III)_{\max}$ and moment of sunrise

	1957	1958	1957 + 1958	
Jan	8°	20°	18°	1,2 h
Feb	35	20	26	1,7
Mar	23	12	13	0,9
Apr	39	38	37	2,5
May	49	13	34	2,3
Jun	29	46	35	2,3
Jul	46	45	39	2,6
Aug	34	39	39	2,6
Sep	23	29	30	2,0
Oct	27	37	33	2,2
Nov	18	17	19	1,3
Dec	16	8	14	0,9

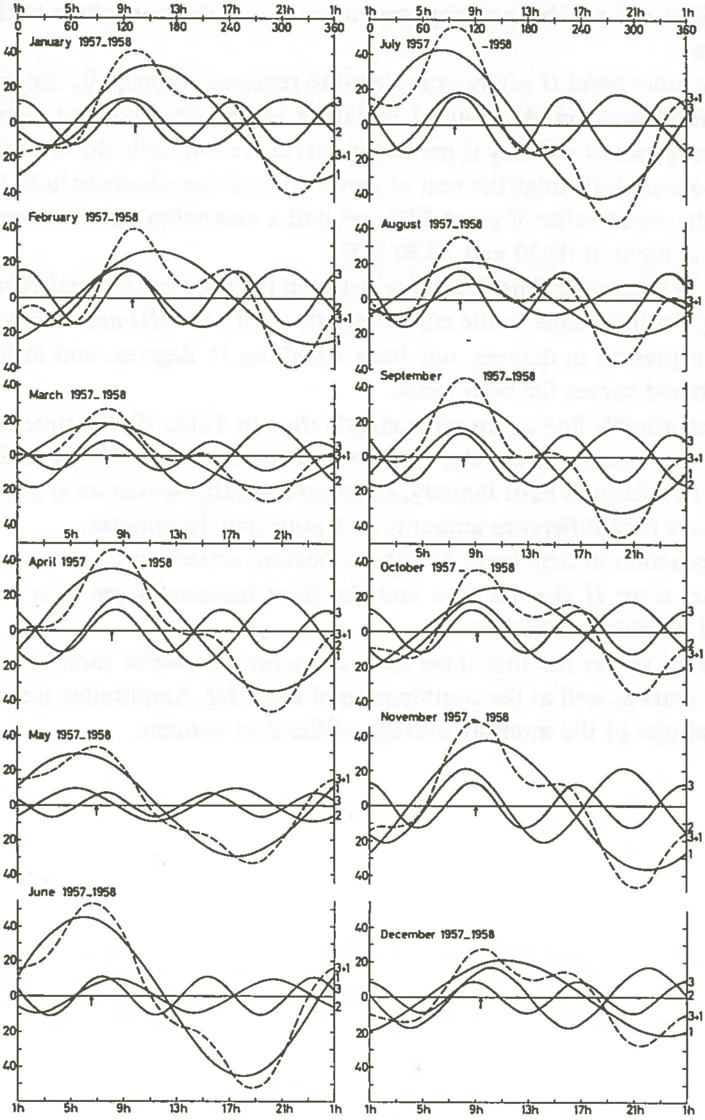

Figure 14. The first three harmonics contributing to the total diurnal dust-variation of the air in Rotterdam and the sum of the first and the third one (dashed curve). Small arrows along the zero-lines in the twelve graphs give the moment at which the latter combination shows its maximum value.
Amplitudes of the various curves are expressed in percentages of the monthly average of the dust content.

other effects and notably anthropogenetic ones will also contribute to these two harmonics.

On the other hand *II* will be considered to represent principally the anthropogenetic influences on the diurnal variation of the dust content, although a certain influence of stability is present in this curve too, as is shown by the shift of the phase angle through the year of about 60 % of that observed in *S*, *I* and *III*. Taking the mean value of φ_2 at 227°, we find a maximum contribution of *II* to the dust content at 08.30 and 20.30 MET.

Table 14 shows the time difference between the moment of occurrence of the morning maximum due to the combined effects of *I* and *III* and the moment of sunrise, expressed in degrees, one hour equalling 15 degrees, and in hours for the combined curves for both years.

It is remarkable how, even more clearly than in Table 10, the time difference is almost constant during the 'summer' season, namely $35° = 2\text{ h }20'$ as an average. For the months of January, February, March, November and December the average time difference amounts to 1 hour and 12 minutes.

The reduction in time lapse during the heating season may be due to the fact that apart from *II* also the first and the third harmonics are then partly determined by human activities.

Figure 14 shows the first three harmonics for the twelve months combined for both years as well as the combination of *I* and *III*. Amplitudes are expressed in percentages of the monthly average of the dust content.

10. THEORETICAL ASPECTS

The diurnal variation of dust content as far as it is determined by the daily stability variation, and as far as the deposition velocity is neglected, can be described in principle by the following equation:

$$\frac{\partial D}{\partial t} = \left[K_0 - K_1 e^{int} \right] \frac{\partial^2 D}{\partial z^2} + Q(z) = K \frac{\partial^2 D}{\partial z^2} + Q(z). \tag{4}$$

In this equation the symbols have the following meaning:

D	total dust content, composed of an average value $\bar{D}$ and a fluctuation D', so that $D = \bar{D} + D'$, $\bar{D}$ being a function of height z only.
K_0	average value of eddy diffusivity.
K_1	amplitude of additional eddy diffusivity. K_0 and K_1 are both taken independent of height, a very crude approximation.
n	angular frequency.
$Q(z)$	distribution of dust source strength, a function of z only.
t	is counted from the moment of maximum stability, i.e. smallest value of K.

In the equilibrium situation, where K_1 is $=0$ we have

$$0 = \frac{\partial \bar{D}}{\partial t} = K_0 \frac{\partial^2 \bar{D}}{\partial z^2} + Q(z) \quad \text{or} \quad \frac{\partial^2 \bar{D}}{\partial z^2} = -\frac{1}{K_0} Q(z). \tag{5}$$

From this it follows:

$$\frac{\partial D'}{\partial t} = -K_1 e^{int} \frac{\partial^2 \bar{D}}{\partial z^2} + (K_0 - K_1 e^{int}) \frac{\partial^2 D'}{\partial z^2}. \tag{6}$$

We now consider

$$K_1 \frac{\partial^2 D'}{\partial z^2}$$

to be of a smaller order of magnitude than

$$K_0 \frac{\partial^2 D'}{\partial z^2} \quad \text{and} \quad K_1 \frac{\partial^2 \bar{D}}{\partial z^2},$$

an assumption that may hold for the third harmonic but probably not with sufficient accuracy for the first one. In order to make calculations not too complicated and taking account of the fact that according to figure 14 the morning maximum of the dust content is almost completely determined by the third harmonic, we henceforth omit the term

$$K_1 \frac{\partial^2 D'}{\partial z^2},$$

so that, with

$$\frac{\partial^2 \bar{D}}{\partial z^2} = -\frac{1}{K_0} Q(z)$$

we get:

$$\frac{\partial D'}{\partial t} = K_0 \frac{\partial^2 D'}{\partial z^2} + Q^*(z)\, e^{int} \tag{7}$$

where

$$Q^* = \frac{K_1}{K_0} Q(z).$$

It follows from the last equation that, apart from the omitted term, a variable eddy diffusivity has the same effect as a variable source strength, the total (virtual) source strength being

$$Q_{\text{tot}} = \frac{K_1}{K_0} Q(z)\, e^{int} + Q(z).$$

We now apply the Laplace transform (see e.g. VOELKER and DOETSCH, 1950):

$$D'(t,z) \supset F(p,q) = pq \int_0^\infty \int_0^\infty D'(t,z)\, e^{-pt-qz}\, dz\, dt. \tag{8}$$

In order to avoid dust transport through the earth's surface we have to take

$$\left(\frac{\partial D'}{\partial z}\right)_{z=0} = 0$$

and further introduce $D'(t, 0) = \delta(t) \supset f(p)$.

Applying the differentiation rules for the Laplace transform we find the transformation of equation (8):

$$F(p,q) = \frac{1}{p - K_0 q^2} \left\{ \frac{\tilde{Q}(q)\, p}{p - ni} - K_0 q^2 f(p) \right\} \tag{9}$$

$\tilde{Q}(q)$ being $\subset Q^*(z)$.

In order to avoid singularities for $p = k_0 q^2$ we have to assume

$$f(p) = \frac{1}{p - ni} \tilde{Q}\left[\sqrt{\frac{p}{K_0}}\right] \tag{10}$$

with

$$\tilde{Q}\left[\sqrt{\frac{p}{K_0}}\right] \subset \frac{1}{\sqrt{\pi K_0 t}} \int_0^\infty e^{-\frac{u^2}{4K_0 t}} Q^*(u)\, du. \quad \frac{p}{p - ni} \subset e^{int}$$

and applying the product theorem we finally get

$$\frac{1}{p} \frac{p}{p - ni} \tilde{Q}\left[\sqrt{\frac{p}{K_0}}\right] = f(p) \subset \delta(t) = \int_0^t d\tau \left\{ e^{in(t-\tau)} \frac{1}{\sqrt{\pi K_0 \tau}} \int_0^\infty e^{-\frac{u^2}{4K_0 \tau}} Q^*(u)\, du \right\}. \tag{11}$$

This equation can be solved exactly by assuming the source $Q^*(u)$ to be exclusively a ground source, $Q^*(u) = Q_0 \eta(u)$ with $\eta(0) = 1$, $\eta(u \neq 0) = 0$, leading to

$$\delta(t) = Q_0 \int_0^t d\tau \frac{1}{\sqrt{\pi K_0 \tau}} e^{in(t-\tau)}. \tag{12}$$

resulting in a phase angle of $\frac{\pi}{4n}$.

We will take $Q^*(u) = Q_0 e^{-\alpha^2 u^2}$ here, however, which seems to be a little more realistic, although it will be necessary to introduce a negative source at some high level in order to avoid a gradual increase of dust content with time. (See also BOUMAN and SCHMIDT, 1961). This assumption leads to the following development:

$$\delta(t) = \int_0^t d\tau \left\{ e^{in(t-\tau)} \frac{1}{\sqrt{\pi K_0 \tau}} \int_0^\infty Q_0\, e^{-\left[\frac{1 + 4K_0 \tau \alpha^2}{4K_0 \tau}\right] u^2} du \right\} =$$

$$= Q_0 \int_0^t d\tau \left\{ e^{in(t-\tau)} \frac{1}{\sqrt{1 + 4K_0 \alpha^2 \tau}} \right\}. \tag{13}$$

Taking t very large, i.e. solving the problem for a moment long after the beginning of the disturbance and putting $\tau = tv$ we get by approximation:

$$\begin{aligned}\delta(t) &= Q_0 \int_0^1 t\,dv \left\{ e^{int(1-v)} \frac{1}{\sqrt{4K_0\alpha^2 tv}} \right\} = \\ &= Q_0\, e^{int} \frac{\sqrt{t}}{2\alpha\sqrt{K_0}} \left\{ \int_0^\infty dv \left[e^{-int\,v} \frac{1}{\sqrt{v}} \right] - \int_1^\infty dv \left[e^{-int\,v} \frac{1}{\sqrt{v}} \right] \right\} \\ &= Q_0\, e^{int} \frac{\sqrt{\pi}}{2\alpha\sqrt{K_0}\sqrt{in}} - Q_0\, e^{int} \frac{\sqrt{t}}{2\alpha\sqrt{K_0}} \int_1^\infty 2\,dw\, e^{-int\,w^2} \end{aligned} \tag{14}$$

where in the last integral v has been substituted by w^2.

$$\int_1^\infty 2dw\, e^{-int\,w^2} = 2\int_0^\infty dp\, e^{-int(1+2p+p^2)} \tag{15}$$

where p equals $w-1$.

$$\begin{aligned} 2\int_0^\infty dp\, e^{-int(1+2p+p^2)} &= 2e^{-int} \int_0^\infty dp \left\{ e^{-2int\,p} \cdot e^{-int\,p^2} \right\} = \\ &= 2e^{-int} \int_0^\infty dp \left\{ e^{-2int\,p} \cdot \sum_{\nu=0}^{\nu=\infty} \frac{(-int)^\nu p^{2\nu}}{\nu!} \right\} = \\ &= 2e^{-int} \sum_{\nu=0}^{\nu=\infty} \left\{ \frac{(-int)^\nu}{\nu!} \int_0^\infty dp \left\{ p^{2\nu} e^{-2int\,p} \right\} \right\} = \\ &= 2e^{-int} \sum_{\nu=0}^{\nu=\infty} \left\{ \frac{(-int)^\nu}{\nu!} \cdot \frac{(2\nu)!}{(2\,int)^{2\nu+1}} \right\} = \\ &= 2e^{-int} \sum_{\nu=0}^{\nu=\infty} \left\{ \frac{(-1)^\nu}{\nu!} (2\nu)! \frac{1}{2^{2\nu+1}} \frac{1}{(int)^{\nu+1}} \right\} = \\ &= e^{-int} \sum_{\nu=0}^{\nu=\infty} \left\{ (-1)^\nu \frac{(2\nu)!}{\nu!} \frac{1}{2^{2\nu}} \frac{1}{(int)^{\nu+1}} \right\}. \end{aligned} \tag{16}$$

And finally:

$$\delta(t) = Q_0\, e^{int} \frac{\sqrt{\pi}}{2\alpha\sqrt{K_0}\sqrt{in}} - Q_0 \frac{\sqrt{\tau}}{2\alpha\sqrt{K_0}} \sum_{\nu=0}^{\nu=\infty} \left\{(-1)^{\nu} \frac{(2\nu)!}{\nu!} \frac{1}{2^{2\nu}} \frac{1}{(int)^{\nu+1}}\right\}$$

$$= \frac{Q_0}{2\alpha\sqrt{K_0}} \left\{\sqrt{\tfrac{\pi}{n}}\, e^{i(nt - \frac{1}{4}\pi)} - \sum_{\nu=0}^{\nu=\infty} \left[(-1)^{\nu} \frac{(2\nu)!}{\nu!} \frac{1}{2^{2\nu}} \frac{\sqrt{\tau}}{(int)^{\nu+1}}\right]\right\}. \qquad (17)$$

Only the first term is periodic, the second goes to zero with increasing t. So $\delta(t)$ shows a phase shift of $\frac{\pi}{4n}$, the same result as for a ground source. Applying this result to the third harmonic, the one that for the greater part determines the moment of occurrence of the morning maximum of the dust content (see figure 14), we find a time difference of 1 hour between the moment of maximum stability and the moment of largest dust content. The moment of maximum stability generally occurring between 30 minutes and one hour after the moment of sunrise, we find a theoretical time difference of about one hour and 45 minutes between the moment of sunrise and the occurrence of maximum dust content. In fact, in reality for the third harmonic this time difference is 1 h 48 m in the average. Compared with the average time difference of 2 hours and 20 minutes during the summer season and 1 hour and 12 minutes during the winter season for the sum of 1st and 3rd harmonics, the present theoretical result looks also very satisfactory, the average time difference for the whole year now being 1 h 52 m. The increase of the time difference during summer and the decrease during winter may, as stated before, be ascribed to human influences, which as a matter of fact contribute to all harmonics. On the other hand we could have added the second harmonic in order to give an adequate description of the total stability effect, without obtaining substantially different results, as far as the moment of occurrence of the maximum is concerned.

11. THE CONNECTION BETWEEN THE DIURNAL VARIATION OF DUST CONTENT AND THE METEOROLOGICAL SITUATION

The relative influence of the first and the third harmonics which are held to represent mainly the influence of atmospheric stability is given in table 13. This relative influence will depend on the diurnal variation of atmospheric stability, i.e. on

$$\frac{K_1}{K_0}$$

according to the foregoing section.

Unfortunately the variation of temperature gradient in the lowest, say, hundred meters of the atmosphere is not known for the two observation years.

The most adequate way to get an impression of the stability variation of the atmosphere is to evaluate the mean diurnal temperature variation for each month. However, this temperature variation cannot be considered an absolute measure in this respect that a certain diurnal temperature range in, say, January will have another significance than the same range would have in May.

We, therefore, compared the monthly averages of the diurnal temperature variations, ΔT, for both observation years separately and tried to find a connection with the differences in dust behaviour of the same months. Taking A_k the amplitude of the k-th harmonic, a comparison between $A_1^2 + A_3^2$ and ΔT has given no significant results. Remembering the fact that II contributes to the phase shift through the year and may be supposed, therefore, to contribute also to the amplitude of the stability range, this negative result is not too surprising.

For this reason it seemed better to compare the temperature range with the total range in dust content. Table 15 contains the temperature range ΔT and the range in dust content ΔD for both years as well as the ratios

$$\frac{\Delta T_{57}}{\Delta T_{58}} = p_T \quad \text{and} \quad \frac{\Delta D_{57}}{\Delta D_{58}} = p_D .$$

Dust ranges have been modified compared with the values given in table 9 by application of the parabola approximation, described in section 8, for the maximum as well as for the minimum value.

Table 15. Comparison between temperature range and range in dust content

	ΔT			ΔD			p_T	p_D
	1957		1958	1957		1958		
Jan	4,5 °C	<	4,9 °C	81,0%	<	84,9%	0,92	0,95
Feb	4,9	<	5,2	106,0	>	69,6	0,94	1,52
Mar	6,8	<	7,7	62,2	<	89,0	0,88	0,70
Apr	9,1	>	7,4	114,0	>	91,1	1,23	1,25
May	8,3	<	8,6	82,1	<	92,8	0,96	0,88
Jun	10,5	>	9,2	121,6	>	113,4	1,14	1,08
Jul	8,1	>	7,7	138,3	>	123,2	1,06	1,12
Aug	6,9	<	7,1	86,3	>	72,4	0,97	1,19
Sep	5,4	<	8,1	92,8	<	105,2	0,67	0,87
Oct	6,0	>	4,9	86,1	>	72,2	1,22	1,19
Nov	4,6	<	5,5	106,3	<	118,1	0,84	0,90
Dec	4,8	<	4,9	82,1	>	72,2	0,98	1,13

From the inequality signs it follows that from 1957 to 1958 ΔT and ΔD change in the same sense in 9 out of the 12 months. The series p_T and p_D can be investigated by both Kendall's and Spearman's rank correlation tests. (See e.g. KENDALL, 1948). The former gives $S=32$, a value between the $2\frac{1}{2}\%$ reliability level (30) and the 1% one (36); the latter after transformation into Student's t-test, gives $t=2,85$, the 1% reliability level being 2,76, the $\frac{1}{2}\%$ level 3,17.

We conclude, therefore, that there exists a significant relationship between ΔT and ΔD, larger values of the former being connected with larger values of

Table 16. Comparison between temperature range and maximum dust content

	ΔT			$D_{\max}$			p_T	$p_{D\max}$
	1957		1958	1957		1958		
Jan	4,5 °C	<	4,9 °C	53,5%	<	56,9%	0,92	0,95
Feb	4,9	<	5,2	70,5	>	44,6	0,94	1,58
Mar	6,8	<	7,7	41,2	<	66,0	0,88	0,62
Apr	9,1	>	7,4	79,5	>	63,1	1,23	1,26
May	8,3	<	8,6	50,1	<	51,8	0,96	0,97
Jun	10,5	>	9,2	71,1	>	65,4	1,14	1,09
Jul	8,1	>	7,7	100,8	>	76,2	1,06	1,33
Aug	6,9	<	7,1	54,8	>	48,4	0,97	1,13
Sep	5,4	<	8,1	67,8	<	74,2	0,67	0,91
Oct	6,0	>	4,9	61,1	>	34,2	1,22	1,79
Nov	4,6	<	5,5	70,3	<	84,1	0,84	0,84
Dec	4,8	<	4,9	49,6	>	42,2	0,98	1,18

the latter for the same months of different years. On the other hand it is especially the maximum value of D that is determined by stability as follows from the parallelism between the moment of its occurrence and the moment of sunrise. We have applied, therefore, the same statistical tests also to the maximum values of D, D_{max}.
Application of Kendall's test results in $S=38$, equal to the $\frac{1}{2}\%$ reliability level and the test according to Spearman-Student in 3,16 ($\frac{1}{2}\%$ level$=3,17$).

It seems therefore, that the connection between stability and the morning dust content maximum is even greater than the connection between stability and the diurnal range of dust content. This may be due to the fact that human activities during day-time partly disturb the effect of stability change.

12. THE DUST CONTENT IN DELFT AND THE HAGUE

Due to courtesy of the Research Institute for Public Health Engineering, T.N.O., the author could apply the analysis of the diurnal dust variation also to dust observations made in two other cities in the western part of the Netherlands, notably in Delft and The Hague. In The Hague two series of observations were made at different places. Delft is situated at a distance of 11 km NW of Rotterdam, about 12 km from the coast, whereas The Hague lies on the coast, one observation point being about 3 km from the sea, the other about 1 km. The observation series in both cities are less complete than those made in Rotterdam, especially the one in Delft.

Table 17 shows the number of observations made in each month for both Delft and The Hague, the maximum possible number being 382, 360 and 336 for 31, 30 and 28 days respectively.

The following operations have been performed with respect to the observations in both cities:

a) The yearly course of the moment of maximum concentration has been determined for the three series.

b) It has been tried to establish a relation between diurnal dust variation and diurnal temperature range from observations made in the same place and in the same month of different years.

In table 18 the moments of maximum concentration are given for all months in which the number of observations for each two-hourly period exceeded twenty. The two years of observations of Rotterdam are included in the table. It should be borne in mind that the observations of The Hague made in 1960 and 1961 refer to another observation post than those made in 1962 and 1963.

The last column, headed *A*, gives the average time of the maximum for the twelve months of the year. The very late time of occurrence of the maximum in The Hague in June 1962 (11 h MET!) does not seem reliable. Deletion of this figure brings the average time of the maximum to 6,6 h for that month.

The points referring to R, H_1, H_2 and D as well as the figures under *A* (with the application of the correction for June) minus 2 are also given in figure 12.

Table 17. Number of two-hourly dust observations per month for Delft and The Hague

	1960		1961			1962		1963
	D	H_1	D	H_1	H_2	D	H_2	H_2
Jan				372		252	321	180
Feb				336		–	335	281
Mar				369		317	372	372
Apr			29	360		360	360	360
May			371	371		372	368	173
Jun			165	360		356	359	
Jul			226	358		54	348	
Aug			259	372			360	
Sep		246	151	356			356	
Oct		312	–	139			366	
Nov		360	19				360	
Dec		185	371		252		371	

The curve connecting them shows a satisfactory parallelism with the one representing the time of sunrise. The fact that the curves *A* and *S* cross in spring and in autumn may be explained by human influences, resulting in a slightly earlier maximum during the cold season and a slight retardation of the maximum during the warm season, compared with the time of occurrence due to stability only.

Tabel 18. Moment of maximum concentration in MET for all months with more than 20 observations for each 2-hourly period, R standing for Rotterdam, H for The Hague, D for Delft and the observation year being added. The column *A* gives the average time of the maximum dust content

	R 57	R 58	H_1 60	H_1 61	H_2 62	H_2 63	D 61	D 62	*A*
Jan		9,96		9,57	9,70			9,65	9,7
Feb	9,56	9,29		9,00	9,25	9,00			9,2
Mar	8,44	7,53		9,16	8,75	8,93		9,10	8,7
Apr	8,93	8,20		7,65	8,57	8,14		7,90	8,6
May	7,08			8,57	6,80		5,76	7,20	7,1
Jun	6,35	8,00		$\boxed{10{,}97}$	6,55			5,56	7,5
Jul	7,10	7,41		8,33	7,44				7,6
Aug	7,83	8,37		9,40	7,91		7,41		8,2
Sep	7,40	8,10		9,17	8,28				8,2
Oct	8,89		9,07		9,07				9,0
Nov		8,88	8,40		9,52				9,3
Dec	10,31	9,47			9,92		9,48		9,8

Finally, the relation between the relative diurnal dust variation in The Hague for the months of February, March and April 1962 and 1963 respectively and the diurnal temperature range, averaged for the same months at the meteorological station of Ypenburg just outside The Hague, has been investigated. The same has been done with respect to the diurnal dust variation in Delft in the months of May 1961 and 1962, again in comparison with the temperature range of Ypenburg. Table 19 contains the results. p_T and p_D, having the same meaning as in table 15, are also given.

Table 19. Relative diurnal variation in dust content ΔD, expressed in percentages of the average monthly value, and in temperature ΔT, for The Hague (January–April 1962 and 1963) and Delft (May 1961 and 1962). Temperatures are taken from Ypenburg, halfway between The Hague and Delft

		ΔD	ΔT	p_D	p_T
February	H_2 62	83 %	4,1°	1,76	0,66
	H_2 63	47 %	6,2		
March	H_2 62	81	5,5	1,59	0,80
	H_2 63	51	6,9		
April	H_2 62	55	6,1	1,12	0,78
	H_2 63	49	7,8		
May	D 61	60	6,4	0,65	1,21
	D 62	92	5,3		

There does not seem to be a clear-cut connection between p_D and p_T for The Hague. From March to April both ratios decrease but February does not fit in this picture. A possible explanation could be that February 1963 was extremely cold, $-3{,}6$ °C compared with $+3{,}6$ °C in February 1962, so that domestic heating was intense, especially during day-time, resulting in a relatively low value of ΔD. On the other hand a temperature range of 6,2 °C is very improbable in the centre of a city during severe frost, domestic heating besides the normal shielding of radiation by buildings, resulting in higher minimum temperatures than at an aerodrome. A reduction of ΔT to 5 °C, which seems to be of the right order of magnitude, resulting in $p_{\Delta T}=0{,}82$ would make the connection between p_D and p_T in accordance with expectation for all three months (see also MITCHELL, 1962).

The observations made in Delft, covering one month only, do not enable to draw any conclusion. It is possible, however, to distinguish between the first and second half of each month, 61 (1), 61 (2), 62 (1) and 62 (2). This procedure leads to:

Table 20. Comparison of the variation of dust content in Delft for the first and second half of May 1961 and 1962

	ΔD	ΔT	p_D	p_T
D 61 (1)	55%	5,6°	0,55	0,96
D 62 (1)	100	5,8		
D 61 (2)	62	7,2	0,71	1,47
D 62 (2)	87	4,9		

p_D and p_T show the same course. The fact that no parallelism is found between ΔD and ΔT in table 19 is probably due to the strong increase of ΔT in the second half of May 1961, both months as a whole not being quite comparable, therefore.

In the same way as was done with respect to the dust observations of Rotterdam we have also compared the maximum value of the dust content, expressed as a percentage of the mean value, with ΔT. The result is given in table 21.

Again we find that February does not fit in the general parallelism that must

Table 21. $D_{\max}$, ΔT, $p_{D\max}$ and p_T for The Hague (February, March and April, 1962 and 1963) and Delft (May, 1961 and 1962)

		$D_{\max}$	ΔT	$p_{D\max}$	p_T
February	H_2 62	146%	4,1°	1,10	0,66
	H_2 63	133	6,2		
March	H_2 62	158	5,5	1,18	0,80
	H_2 63	134	6,9		
April	H_2 62	141	6,1	1,05	0,78
	H_2 63	134	7,8		
May	D 61	140	6,4	0,86	1,21
	D 62	163	5,3		

Table 22. Comparison of maximum dust content for the first and second half of May, 1961 and 1962

	$D_{\max}$	ΔT	$p_{D\max}$	p_T
D 61 (1)	133%	5,6°	0,78	0,96
D 62 (1)	171	5,8		
D 61 (2)	141	7,2	0,96	1,47
D 62 (2)	156	4,9		

be expected between $p_{D_{\max}}$ and p_T, but here the discrepancy is somewhat smaller. Here a reduction of $\Delta T(1963)$ from 6,2 °C to 5,2 °C would make the picture consistent.

Splitting up again the results for Delft in the first and the second half of the month we now get the results of table 22.

Comparing the first and second half of the month for each year we find from the figures in table 22: $p_{D_{\max}}(1961)=0{,}94$ and $p_{D_{\max}}(1962)=1{,}10$ against $p_T(1961)=0{,}78$ and $p_T(1962)=1{,}18$. Both these results and those given in table 22 indicate that there exists a relation between ΔT and $D_{\max}$.

13. CONCLUSIONS

The analysis of the dust content measurements made in three Netherlands cities reveal that the contamination of city air strongly depends on atmospheric circumstances. This dependence is connected with the fact that the cleaning of the air, at least in the central part of a city for the greater part takes place by upward diffusion of the pollution produced by industries, domestic heating and traffic. This upward diffusion can be caused by mechanical turbulence due to the disturbance of the windfield by the rough terrain or by static instability or, generally, by the combined effect of the two.

The influence of windforce as well as the influence of stability was proved to be highly significant.

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SUMMARY

The results of two years hourly or bihourly dust observations in the center of Rotterdam have been analysed with regard to a connection with meteorological and other circumstances.

From this analysis the following conclusions can be drawn.

1. Relatively large differences occur between the annual variation of the dust content of the air in 1957 and in 1958. It appears that these differences can be related to differences in meteorological circumstances during both years, at least partly.

Notably differences in wind direction are of importance in relation with the asymmetric distribution of dust sources around the observation point. Moreover, wind speed and rainfall play a role. High wind speeds and large amounts of precipitation both result in a decrease of dust content. This is elaborated into detail in section 2.

2. The variation of the dust content of the air in Rotterdam through the week shows the same pattern as found elsewhere. Section 3.

3. The influence of wind force on the dust content is investigated in more detail in section 6. During the winter half year dust content appears to decrease with increasing wind force. In the summer half year such an effect can hardly be detected, however.

This difference in behaviour is assumed to be due to the fact that during the winter half year the upward diffusion of dust is almost completely caused by dynamic turbulence which becomes more intense with increasing wind force, whereas in the summer half year vertical diffusion is for the greater part due to frequently occurring instability. During the latter season a relation between diffusion rate and wind force is difficult to find, therefore.

4. In section 7 the influence of wind direction on the dust content of the air is analysed. It appears that the fact that on-shore winds cause the stratification of the lower layers of the atmosphere to become stable in the cold season and unstable in the warm season determines the behaviour of the dust content in both seasons for an important part.

The ratio between the dust content in winter and in summer is larger during situations with on-shore winds than it is in the average for all wind directions. It seems improbable that this difference can be ascribed to an asymmetric distribution of dust sources from domestic heating.

5. An extensive analysis has been made of the diurnal variation of the dust content of the air in Rotterdam (sections 8 through 11). A morning maximum occurs which shifts through the year almost parallel with the moment of sunrise, notably between 7 h MET in June and 10 h MET in December and January. This is too large a timeshift to be ascribed exclusively to human activities. A mathematical analysis of the effect of a periodical stability variation on the behaviour of air pollution in a big city gives results which are in good agreement with the observations.

Finally, in section 12 dust observations made in The Hague and in Delft have been considered. The relatively short observation series do not permit a detailed investigation as in the case of Rotterdam, but it can be stated that notably the diurnal variation of the dust content of the air in the former cities is similar to that in Rotterdam. Especially the shift of the time of occurrence of the maximum through the year shows the same pattern in all three cities.

SAMENVATTING

De resultaten van twee jaar uurlijkse of twee-uurlijkse stofwaarnemingen in het centrum van Rotterdam werden geanalyseerd op een samenhang met meteorologische en andere omstandigheden.

Uit deze analyse kunnen de volgende conclusies worden getrokken.

1. Er komen betrekkelijk grote verschillen voor tussen de jaarlijkse gang van het stofgehalte van de lucht in 1957 en van dat in 1958. Een nadere beschouwing van deze verschillen toont, dat zij voor een gedeelte kunnen worden toegeschreven aan verschillen in de meteorologische omstandigheden gedurende de beide jaren. Met name gaat het hierbij om de windrichting (in verband met de asymmetrische verdeling van de stofbronnen rond het waarnemingspunt), de windsnelheid en de regenval. Grotere windsnelheid en grotere neerslaghoeveelheid leiden beide tot een verminderde stofvangst. Eén en ander is nader uitgewerkt in hoofdstuk 2.

2. Het verband tussen het stofgehalte van de lucht in Rotterdam en de dag van de week is voor de beide onderzochte jaren overeenkomstig hetgeen elders werd gevonden. Hoofdstuk 3.

3. De invloed van de windkracht op het stofgehalte wordt nader onderzocht in hoofdstuk 6. In het winter-halfjaar blijkt er een duidelijke afname te bestaan van het stofgehalte met toenemende windkracht. 's Zomers is dit effect niet of nauwelijks aantoonbaar.

De oorzaak van dit verschijnsel moet worden gezocht in het feit, dat in het winterhalfjaar de opwaartse diffusie van het stof vrijwel geheel een gevolg is van dynamische turbulentie, die met groter wordende windkracht in intensitieit toeneemt. In het zomer-halfjaar is de opwaartse diffusie vooral een gevolg van frekwent voorkomende onstabiliteit, waardoor een samenhang tussen diffusie en windkracht veel moeilijker valt aan te tonen.

4. In hoofdstuk 7 wordt de invloed van de windrichting op het stofgehalte nauwkeuriger onderzocht. Het blijkt, dat het feit, dat de atmosfeer tijdens oplandige winden in het winter-halfjaar aanmerkelijk stabieler pleegt te zijn dan tijdens het zomer-halfjaar, duidelijk in het verloop van het stofgehalte is terug te vinden.

De verhouding tussen het stofgehalte in de winter en de zomer is tijdens situaties met oplandige winden groter dan gemiddeld over alle windrichtingen het geval is. Het is onwaarschijnlijk, dat dit verschil zou moeten worden toegeschreven aan een asymmetrische verdeling van stofbronnen samenhangend met huisverwarming.

5. Een uitgebreide analyse is verricht m.b.t. de dagelijkse gang van het stofgehalte van de lucht in Rotterdam (hoofdstukken 8, 9, 10 en 11). Er treedt een ochtend-maximum op in het stofgehalte, dat vrijwel parallel met het moment van zonsopkomst door het jaar verschuift, en wel van ongeveer 7 uur MET in juni tot 10 uur MET in december en januari. Dit tijdsverschil is te groot om het uitsluitend op rekening van menselijke activiteiten te kunnen schrijven. Een wiskundige analyse van het effect van een periodieke stabiliteitsverandering op het gedrag van luchtverontreiniging in een grote stad, leidt tot resultaten, die goed met de waarnemingen overeenstemmen.

In hoofdstuk 12 is tenslotte nog aandacht besteed aan stofwaarnemingen in 's Gravenhage en Delft. De betrekkelijk korte waarnemingsreeksen maken een uitvoerig onderzoek, zoals in het geval van Rotterdam, niet mogelijk, maar wel kan worden gesteld dat met name de dagelijkse gang van het stofgehalte in eerst genoemde beide steden met die welke in Rotterdam wordt gevonden, overeenstemt. In het bijzonder vertoont het verschuiven van het maximum in de loop van het jaar in alle drie steden hetzelfde patroon.

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