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A THREE-DIMENTIONAL TRANSPORT MODEL FOR AIR POLLUTION IN AN URBAN AREA WITH APPLICATION TO SO_2 CONCENTRATION IN OSLO

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FOREWORD

The work presented in this paper is a part of a larger investigation of the SO_2 concentration in Oslo. The leader of the project has been E. Joranger. The project has been financially supported by the oil companies in Norway.

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1 INTRODUCTION

The Norwegian Institute for Air Research (NILU) has performed an investigation of the ambient air concentration of SO_2 in Oslo, and its relation to emission and weather conditions.

During the period 1959/1963, the SO_2 concentration has been measured in Oslo by W. Lindberg (1). NILU's investigation was financially supported by the oil companies in Norway, and the intention was to establish the trend in the ambient SO_2 concentration from this periode to the winters 1969/70 and 1970/71. Further, the intention of NILU's investigation was to develop a model that described the connection between the emission of SO_2, the ambient air concentration and the weather conditions (wind and temperature stratification).

To establish this connection in a realistic way, it was found necessary to study representative short term variations in the SO_2 concentration. As far as the author knows, this has not been done before with reportable success. Instead, work has been carried out to model longer term average concentration which is important in air quality considerations.

In many of the applied models, a Gaussian diffusion formulae is used to estimate the dispersion from a large number of single point sources or groups of point sources within the urban area (2) (3). A Gaussian diffusion formula is known to describe well the dilution of pollutants under certain simplified wind conditions. On the other hand, these simplified wind conditions are not realistic in an urban area. The existence of a convergence zone over the centre of the city is well known (4), and this ought to be taken into consideration.

The pollution concentration in an urban area depends on both meteorological and chemical processes within the area. Emission of pollutants is often connected to emission of heat.

In that way, both the chemical and meteorological conditions are changed due to the emission. The extrapolation of measurements of the ambient air concentration to other conditions of emission is difficult without knowing the importance of the different processes that cause these changes.

In a comprehensive system approach to abatement strategy, the connection between a reduction in emission and the change in ambient air concentration is approximated by a linear relationship (5). The air quality standards are set according to biological effects that primarily depend on the concentration near the ground. When a local problem is considered, it is the ground level concentration that has to be taken into account. On a larger scale, the total emission has to be considered together with the cleaning processes of the atmosphere.

In the city of Oslo, we are studying a local air pollution problem. The horizontal transport of pollution will not carry the pollution away from the ground level although it will be diluted. Systematic vertical motion will transport the pollution away from the ground level more rapidly. Therefore, it is important to estimate the relative significance of these two transporting components.

It is rather difficult to analyse the chemical processes that lead to a transformation of the pollution components. As a first approximation, we have estimated a sink of SO_2 in Oslo to be dependent on the SO_2 concentration alone.

H. Reiquam was the first to perform model-calculations in Oslo during his stay in Norway in 1968 (6). These calculations showed that the use of a finite grid system (a box model) might be useful in Oslo. It might be said that we continued his work in our model studies during the winters of 1969/70 and 1970/71. A preliminary model was established and tested after the first winter,as a numerical solution of the continuity equation, applied to SO_2 as the pollution component (7). A stream-function was used to describe the horizontal windfield, and a sink term was made proportional to the concentration. The vertical flux of SO_2 was incorporated in this term as a first approximation, and the factor of proportionality was made dependent on the vertical temperature stratification. The value of this factor was chosen in order to match the observed and calculated concentrations. The factor had to be given a very high value which indicated that systematic vertical motions are important as a transport component. This conclusion was supported by detailed wind observations in a number of case studies.

2 MATHEMATICAL FORMULATION OF THE MODEL

As a mathematical frame for our model studies, the continuity equation for the pollution component (eq. 1) is used.

$$(1) \quad \frac{\delta q}{\delta t} = - \nabla_h \cdot (\vec{v}_h q) - \frac{\delta}{\delta z}(wq) + \nabla_h \cdot (K_h \nabla_h q) + \frac{\delta}{\delta z}\left(K_z \frac{\delta q}{\delta z}\right) + \text{sources} + \text{sinks}$$

t : time

x, y, z : orthogonal coordinates with unit vectors, $\vec{i}$, $\vec{j}$, $\vec{k}$

q : pollution concentration

K_h, K_z : horizontal and vertical diffusion coefficients

$\vec{v}_h = u\vec{i} + v\vec{j}$: horizontal velocity

$\nabla_h = \vec{i}\frac{\delta}{\delta x} + \vec{j}\frac{\delta}{\delta y}$: horizontal gradient operator

w : vertical velocity

In an urban area, there exist a lot of small sources at different levels up to a certain height H. Within this area the buildings and the heat sources at different levels lead to enhanced turbulence and a mixing of the air. In the computations, the mean concentration in this lowest part of the atmosphere is considered.

The equation is integrated vertically:

$$(2) \quad \frac{\delta\bar{q}}{\delta t} = - \overline{\nabla_h (\vec{v}_h q)} - \frac{(wq)_H}{H} + \overline{\nabla_h \cdot (K_h \nabla_h q)} + \left(\frac{K_z}{H} \frac{\delta q}{\delta z}\right)_H + \overline{\text{sources}} + \overline{\text{sinks}}$$

$(\bar{\ })$: the mean value in the lowest part of the atmosphere with height H.

The horizontal windfield is separated in two parts. One divergent ($\vec{v}_\chi$) and one non-divergent part ($\vec{v}_\Psi$)

$$(3) \quad \vec{v}_h = \vec{v}_\chi + \vec{v}_\Psi \; ; \quad V_x = \nabla_h \chi \; ; \quad \vec{V}_\Psi = \vec{k} \times \nabla_h \Psi$$

The divergent part is described by a velocity potential χ and the non-divergent part is described by a stream function Ψ. Observed winds at the boundary are used to estimate the stream function along the boundary after correction with respect to the divergent part of the velocity.

A town represents a permanent heat source relative to its surroundings, and will cause vertical motions. As a first approximation it is proposed to put the horizontal divergence ($\nabla_h \cdot \vec{v}_h$) proportional to heat sources or some parameter describing the heat sources.

$$(4) \quad \nabla_h \cdot \vec{v}_h = \nabla^2 \chi = a \cdot Q$$

Q : heat sources in the region
a : empirical factor of proportionality

The factor of proportionality must be estimated empirically for each region.

The separation of the horizontal wind field into one convergent and one non-convergent part is not yet properly defined. As a starting point, the velocity potential is defined to be zero along the boundary. It may be shown that in this way, the kinetic energy connected to the convergent part of the velocity is kept at a minimum.

The effect of meteorological processes on a larger scale are taken into consideration by measuring or estimating the wind along the boundary. The measured boundary values are ajusted with respect to the convergent wind-field. The remaining part is used to estimat the stream function along the boundary. To estimate the stream-function within the region, the following equation is used:

(5) $\nabla^2\Psi = 0$

A way to estimate the vorticity within the region has not been found without taking a more complete set of the hydrodynamical equations into consideration. The intention of the present wind approximation is to calculate the air pollution concentration within an urban area, and it is believed that this concentration is strongly dependent on the vertical motion, but not very sensitive to small changes in the horizontal wind-direction. The mentioned approximations represent a better approximation than the assumption of an homogeneous wind-field in the urban area, when the wind-field is weak.

A finite difference approximation of equations (2), (3), (4) and (5) may be used as a mathematical frame for the study of short term air pollution variations in an urban area.

Forward differences in time combined with upwind differences in space seem to be appropriate for eq. 2 if slow fluctuations in the concentration are considered. In an urban area, this often represents the more important variations. A relatively large artificial diffusion is built into the finite difference form. On the other hand, this form is simple, stable and ensure mass consistence.

3 DESCRIPTION OF THE OSLO-REGION AND THE MEASUREMENTS IN OSLO

The Oslo region is shwon in Fig.1. The urbanized area is concentrated in about 60 km^2 and about 400 000 people are living there. The city of Oslo is surrounded by hills (height 3-500 m) on one side, and the Oslo-fjord on the other.

During winter time, this system of topography and local heat sources induce a local wind system that may create air pollution problems. This happens during inversion situations and, statistically, a close connection is found between the vertical temperature gradient and the SO_2 concentration (8).

Six termographs were placed along the hillside of Holmenkollåsen and were used together with the temperature recordings at the permanent meteorological stations to estimate the vertical stratification.

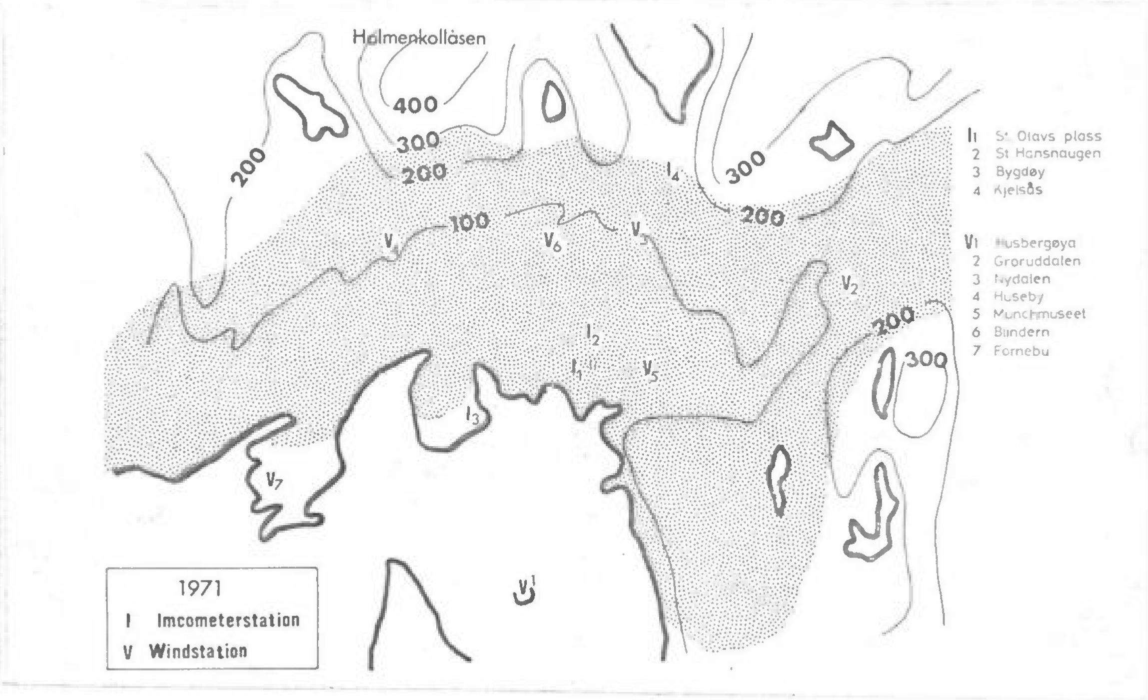

Fig. 1: The area of Oslo with measuring stations

The site of the continuous wind measuring stations (V_1, V_2, V_3 and V_4 on Fig. 1) were chosen in order to measure the wind through the main valleys. Beside, two wind stations were placed in the centre of the city in addition to the permanent meteorological stations at Blindern (V_6) and Fornebu (V_7).

The air quality survey consists of 25 stations measuring the daily mean SO_2 values together with the dust on filter (by light reflection). At four stations, the mean SO_2 concentration was measured each half hour (Braun and Lübbe imcometer). The imcometer and wind stations are marked in Fig. 1. Two of them are placed in

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the centre of the city, while the other two are placed north and south of this centre respectively.

These measurements were adapted to the model studies and the observation region is devided into a gridsystem shown in Fig 2.The regions with high elevation are excluded from our computations.

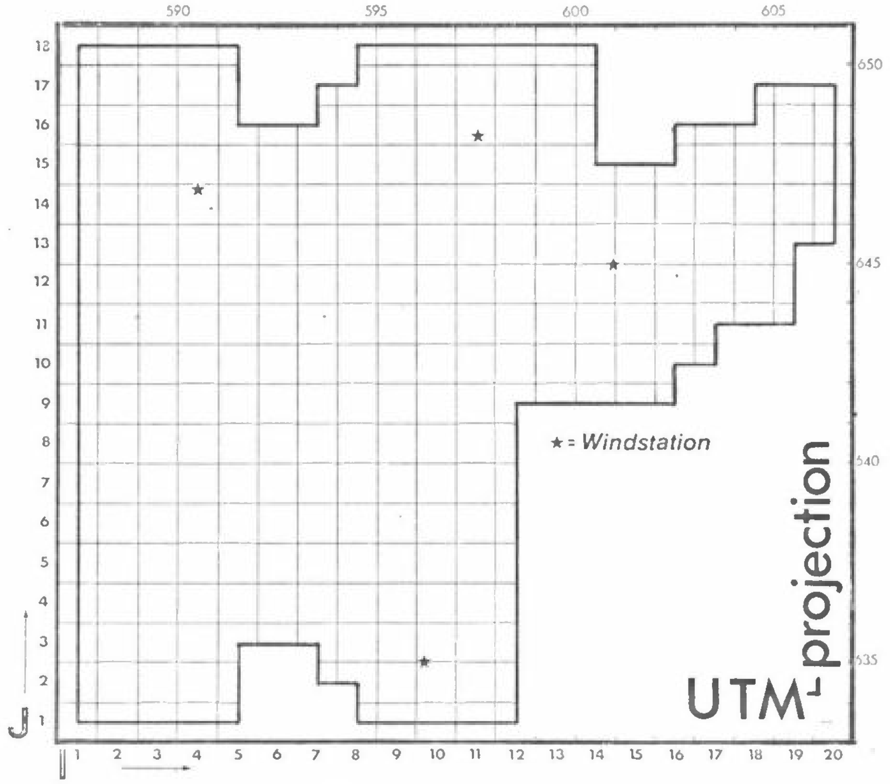

Fig. 2: The grid system

The grid distance is 1 km,and,in the finite difference approximation of eq. 2, a forward time step and an upwind finite difference system were used.

The finite difference approximation introduces an artificial diffusion. Reasonable estimates of the actual diffusion coefficient indicate that the diffusion term in equation 2 is small, compared with the artificial diffusion on a km scale. Therefore, the diffusion terms are left out of the computations.

An emission inventory up to 1970 was carried out by the oil companies in Norway. A result of this inventory has been an estimation of the delivery of sulphur in oil to each square km within the region during the first three months of 1970. This estimate is shown in Fig. 3.

These data were extrapolated to the first three months of 1971, using data from the oil companies. The result is given in Fig. 4.

To obtain a better understanding of the emissions and their time fluctuations, inquiries were made to a number of large oil consumers in the region. Although the investigation is not finished yet, it was found acceptable to use the data as an estimate of the SO_2 emission in the model calculations. There are uncertainties, but it is not believed that these will have any large influence on the computation.

The emission survey has also shown that the emission of SO_2 in Oslo is mainly due to domestic heating. There exists a large number of small sources and few isolated stacks. The emission height is connected to the height of the houses in the region. In this way, the sources of SO_2 in the Oslo region may be considered as volume sources and the height of the volume is connected to the maximum emission height in each square (1 side: 1 km).

4 WIND MODEL FOR OSLO

In order to estimate the wind field along the ground in Oslo from the permanent net of wind-measuring stations, detailed investigations of the wind and temperature field were performed in 11 separate case studies.

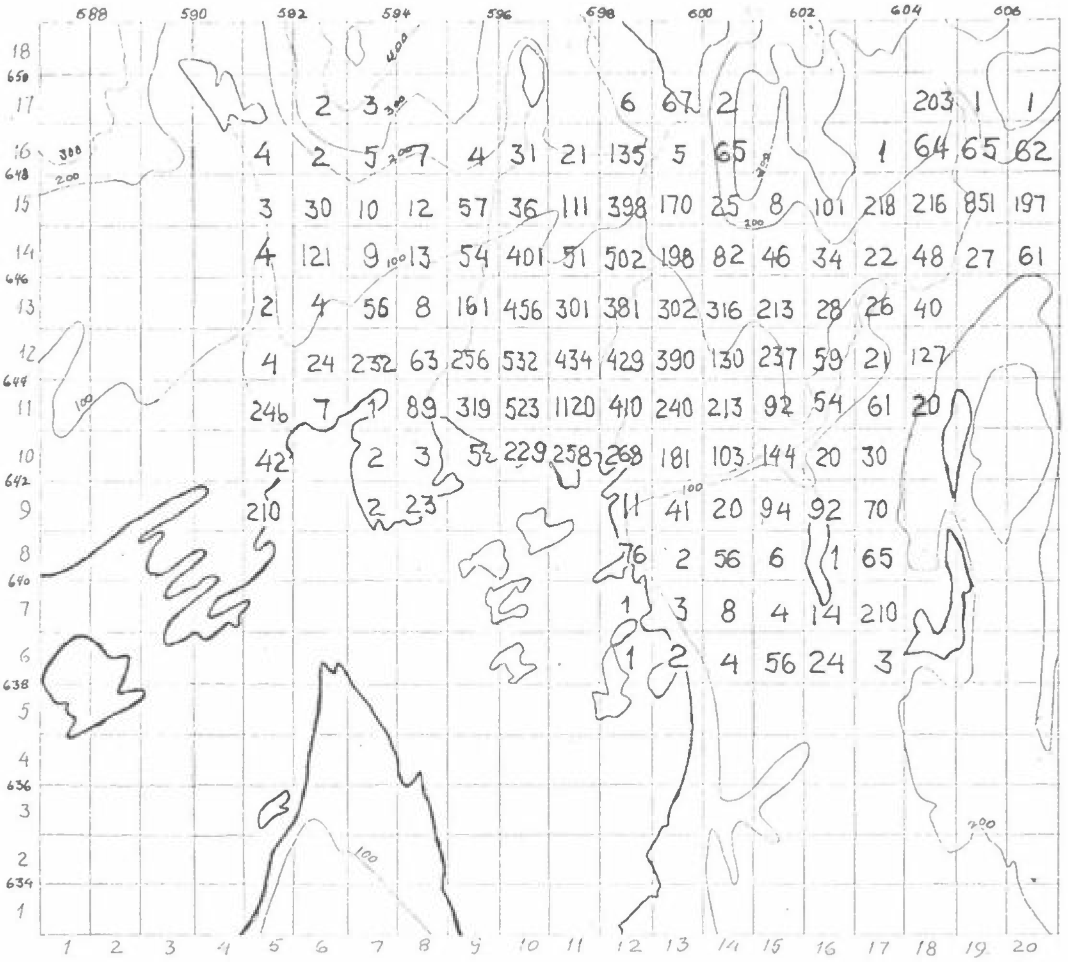

Figure 3 Delivery of sulphur in oil Jan.-March 1970 (100 kgS/km²)

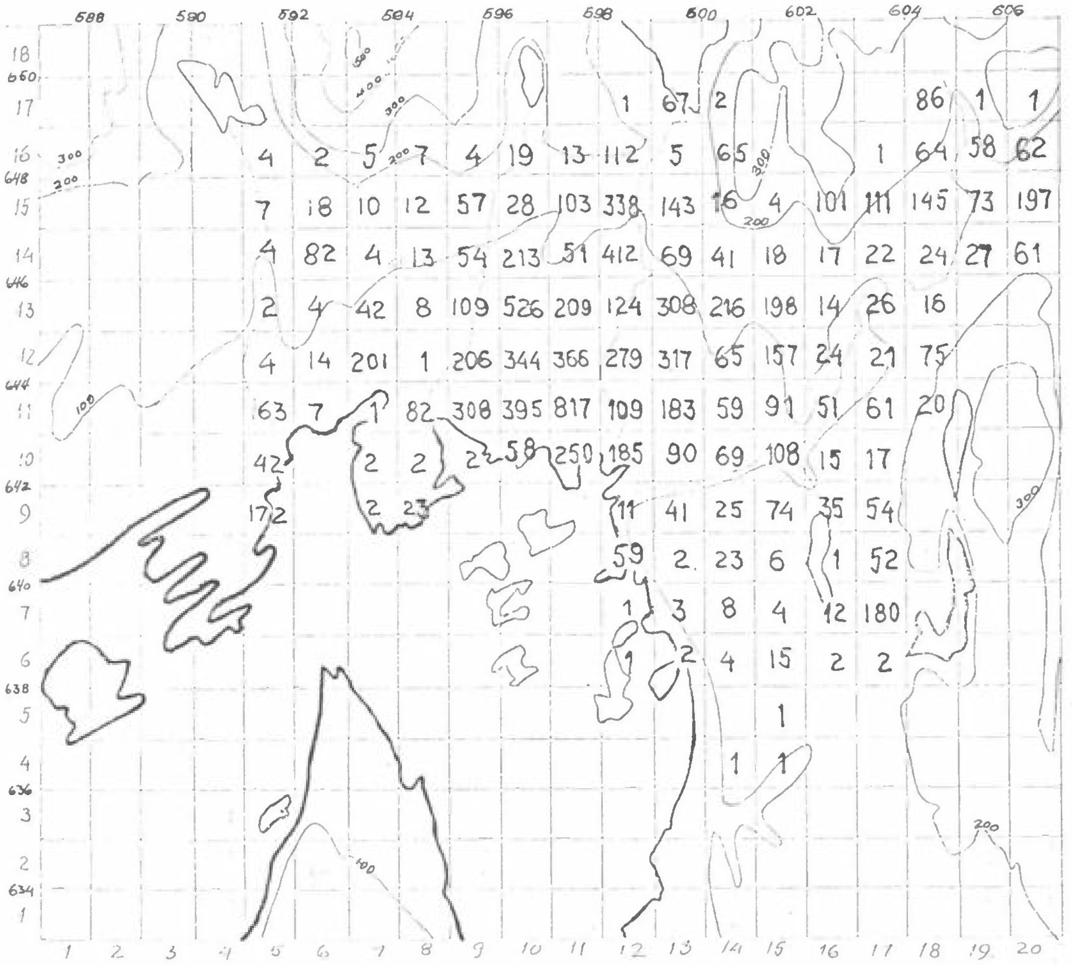

Fig. 4 Delivery of sulphur in oil January-March 1971 (100 kgS/km²)

In these case studies, cars were used along specified routes to measure wind and temperature. In this way, the wind and temperature fields in the area were measured within two hours. The wind variation with height was measured with a wire-sonde. The wire sonde registration showed that the net of thermographs along the hillside of Holmenkollen measured vertical temperature stratification fairly well when local effects on single ground stations were taken into consideration. In inversion situations, a shallow atmospheric layer with neutral temperature stratification was observed over the centre of the city.

Films and photographs were also used to a large extent in the case studies to register the extent of the air pollution. From this material, it was pointed out that there exist a systematic lifting of the pollution in the area (9).

Along the ground level, a more or less well developed heat island (1-3°C) was found in the centre of the city.

On cold days, the open Oslo-fjord represents a considerable heat source and a convergence zone in the area.

The windfield was thoroughly analysed on the 18th of December 1970 and on the 6th of January 1971. An estimation of the divergence along the ground showed that this was mostly negative. Further, it seemed to be a reasonable approximation to set the convergence proportional to the emission of SO_2 over the city and proportional to the temperature difference between air and water over the open Oslo-fjord. The empirical manifestation of equation (4) in Oslo was:

$$(6) \qquad \nabla \cdot \vec{V}_h = \nabla^2 \chi = \begin{cases} a_1 \, Q_{SO_2} & \text{over the centre of the city.} \\ a_2 \, (T_A - T_W) & \text{over the open Oslo-fjord, when } (T_A - T_W) < 0 \end{cases}$$

Q_{SO_2}: areal sources of SO_2 in the region
$T_A - T_W$: Temperature difference between air and water

a_1 : $- 1,5 \cdot 10^{-5} \; s^{-1} \; (\text{ton } S/(km^2 \cdot 3 \text{ months}))^{-1}$
a_2 : $+ 3,0 \cdot 10^{-4} \; s^{-1} \; deg^{-1}$

The values a_1 and a_2 are regarded as empirical estimates of the combined effect of gravitational forces and heat sources in the area. It is believed that a_1 and a_2 are functions of other meteorological parameters within the region (f. ex. inversely proportional to the stability in the air), but no definite relationship of this kind was found in the present investigation.

To estimate the stream function describing the non-divergent wind field in Oslo, the wind measurement from each of the valleys was used. The wind observations were corrected with respect to the convergent wind field, and the corrected measurements on Husbergøya V_1, Groruddalen V_2, Nydalen V_3 and Husby V_4 were used to estimate the streamfunction,along the boundary,in their neighbourhood. No air stream was allowed to cross very steep hillsides (for example Holmenkollåsen).

The computed and measured wind directions in the area are compared in 11 case studies. In the Fig. 5-8, the arrows (↑) show the calculated wind directions in each grid point. The hached arrows show observed wind directions at the region time. The observation are mainly built on the drifting of smoke from Chimneys (10-20 m above ground level), but also on the drift of soap bobbles about 2 m above the ground. In the lower right part of the Figs. 5-8, the measurements from the termographs show the dependence of temperature on height. Date and time of the case study is given on each figure (5-8). A short description of the calculation and observation in each of the case studies are given.

Case study 1: 7.p.m., 11th December 1970 (Fig. 5)

The weather was foggy, and there was a stable temperature-stratification. The air movements are mainly from the south, and it is seen that a point of stagnation is moved to the north, relative to the maximum convergence zone over the centre of the city and the fjord according to eq. 6. In the north-eastern valley (Groruddalen), the wind is weak and undefined.

The main features of the observations are comparable to the computed values. Near the fjord in the western part of the area

(Lysaker), the observed wind direction is towards the fjord while the computations show an air flow from the fjord. On the other hand, the computations are comparable with the observations made in the north-western part of the area.

The difference between the observed and calculated values is probably due to local canalizing effects and a katabatic effect between the warm fjord and the cold land. An increase in the heat source effect of the fjord that would be necessary to attain the observed picture would be unrealistic.

Case study 2: 12 a.m., 18th December 1970 (Fig.6)

The fjord does not represent a heat source in this case because of the high air temperature. The cooling effect of the fjord will probably be effective only in a shallow part over the water and it is not believed to have any impact on the general wind field in the area. The vertical temperature stratification is stable (1 deg/100 m) with a neutral part over the centre of the city. The point of stagnation falls together with the maximum zone of convergence over the centre of the city.

The main features of the observed and calculated wind fields correspond. In the area over the fjord, there are discrepancies that might be due to special effects over the fjord that are not taken into consideration.

Case study 3: 11 a.m., 4th January 1979 (Fig. 7)

The vertical temperature stratification in the area is stable with a neutral part over the centre of the city. The general wind field shows a weak wind from the west. Because of this, the stagnation point is moved north-eastwards, relative to the maximum convergence zone. In this case, the observed and calculated winds correspond well.

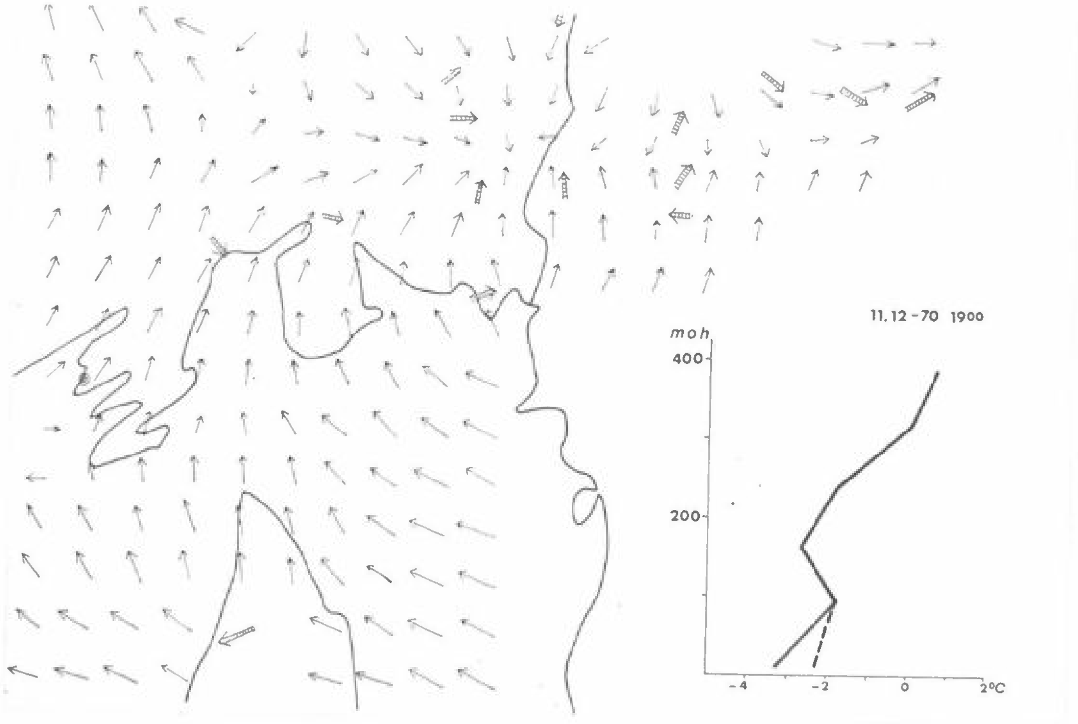

Fig. 5

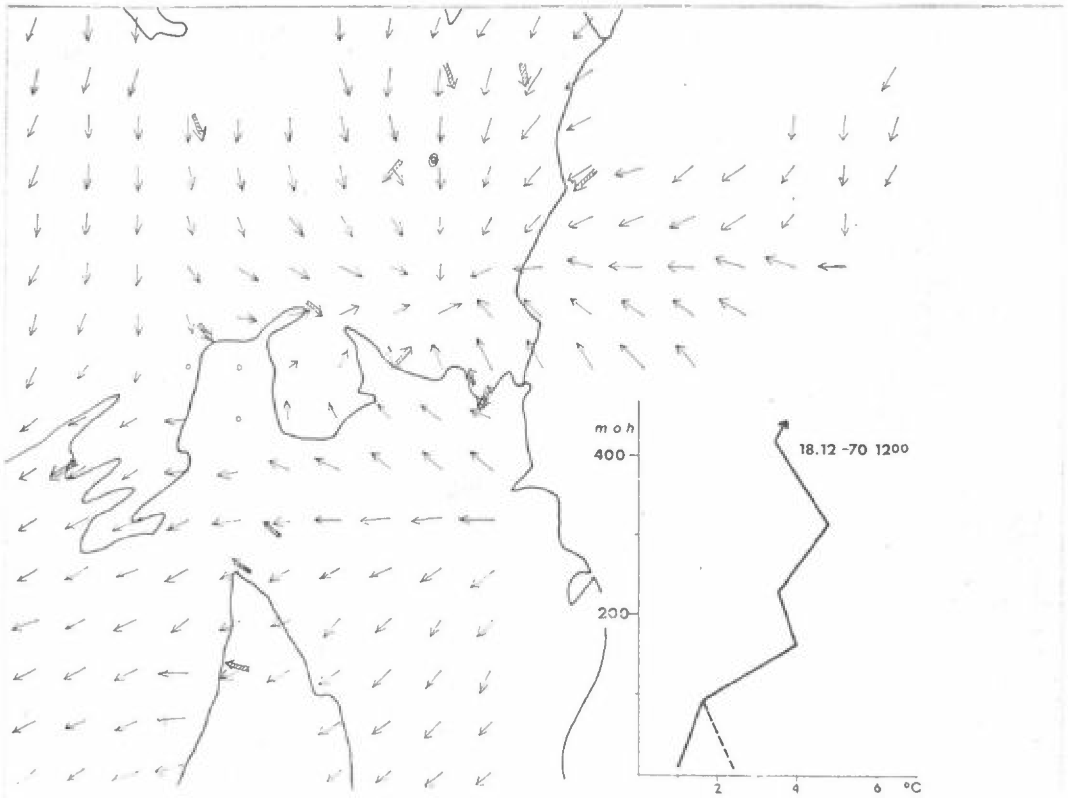

Fig. 6

Case study 4: 3 p.m., 5th January 1971 (Fig. 8)

Largely, the temperature stratification seem to be neutral up to more than 200 m above sea level. Above this level, the air masses seem to be stable. Generally, it may be said that the correspondance between the calculated and observed wind directions are good. An observation at the peninsula in the southern part of the area differs from the calculated wind direction.

The computed wind directions in that part of the fjord are due to the wind observation in the south-eastern part (V_1) and to the compensation zone in the south-western corner. The computed wind velocities over the fjord are very weak, and if one of the measured winds at the boundary is not representative, it may change the wind direction in the south western area completely.

Case study 5: 10 a.m., 6th January (Fig. 9)

The air was very cold and very stable in the lowest part of the atmosphere. A very well developed heat island was observed over the center of the city. Besides, an air stream from the north-east along the ground is well developed (katabatic wind). In this situation, some serious discrepancies are observed between calculated and observed winds.

In the eastern and southern part, the correspondence is good. Over the centre of the city a tendency of stagnation is observed that is not computed. This may be of local importance.

In the western part of the region, a calculated stream towards the fjord does not compare with the observed winds. The observed air flow is directed along the isoterms where no heat sources exist and, in this way, there is correspondance between the wind and temperature observations in the area.

It might be noted that the wind blows along the direction of the geological structures in the area, and that small valleys might have a canalizing effect when the stability is high.

The rotation of the earth (Coriolis-force) may have an effect on the air streams in the area and explain the discrepancies.

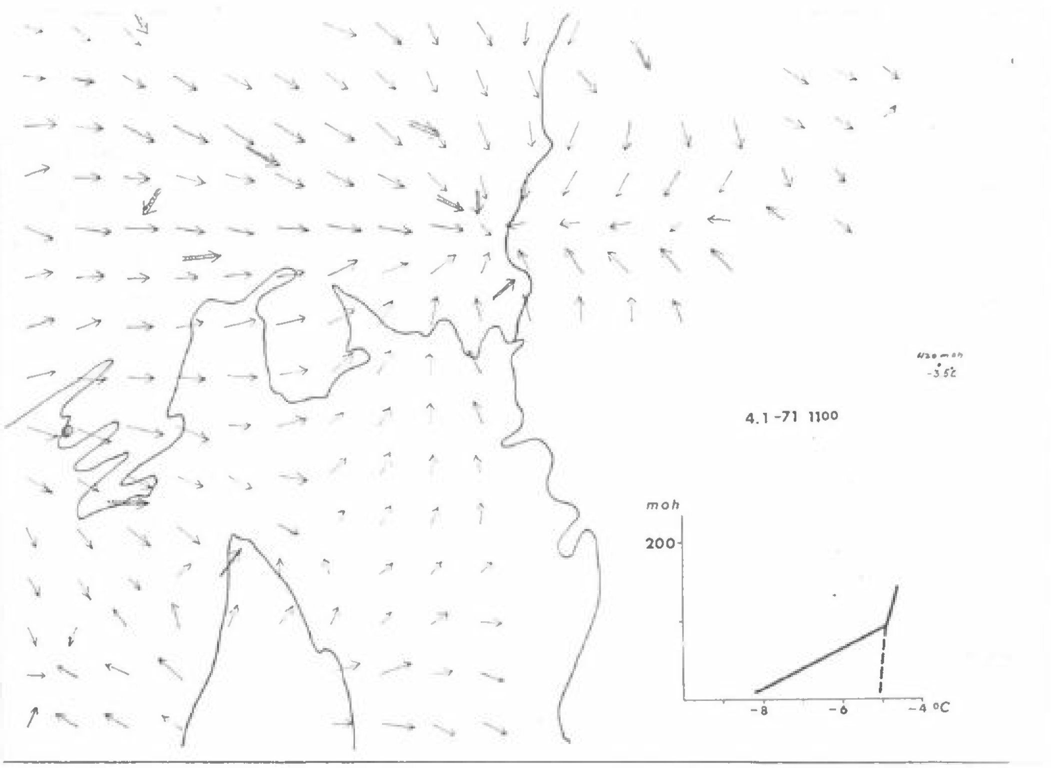

Fig. 7

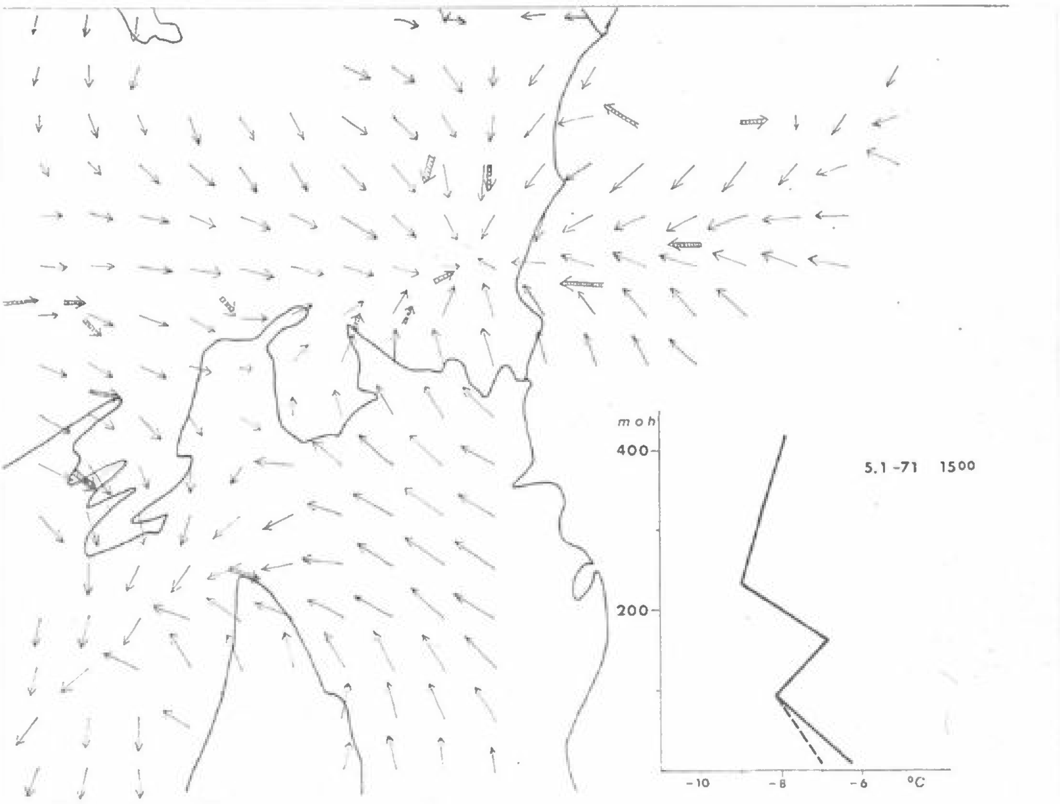

Fig. 8

Case study 6: 1 p.m. 29th January 1971 (Fig 10)

The vertical temperature stratification is near neutral. The computed and observed values compare well at 1 p.m.. On the other hand, the wind field is not stationary. The observed and calculated wind field earlier in the day did not compare well. The present model does not cover transient wind fields. This is evident for example by the compensating zone in the south-western corner of the region and by the approximation of quasi stationa-

Case study 7: 12 a.m. 4th February 1971 (Fig. 11)

The vertical temperature stratification seems to be very stable in the lowest part of the atmosphere (6 deg/100 m). The air flow comes mainly from the south. The wind force is high enough so that no stagnation point is observed over the centre of the city. It seems that the wind station in Nydalen (V_3) (on which the computations are based) has been influenced by a local wind field which could have caused the discrepancies between observed and calculated winds. The observed wind at Blindern (V_3) indicates that an air stream from south is realistic in the northern part too.

Case study 8: 12 a.m. 10th February 1971 (Fig. 12)

The vertical temperature structure is neutral. The main features in the observed wind field is matched in the calculation. In the western part, the observed wind directions are more perpendicular to the shoreline than calculated. Discrepancies like these are often observed and seem to be due to local effects in that part of Oslo.

Case study 9: 12 a.m. 23rd February 1971 (Fig 13)

The vertical temperature stratification is moderately stable. The general air stream is from the south-west and the stagnation point is moved to the north-east relative to the maximum convergence zone. The calculated and observed wind directions match well.

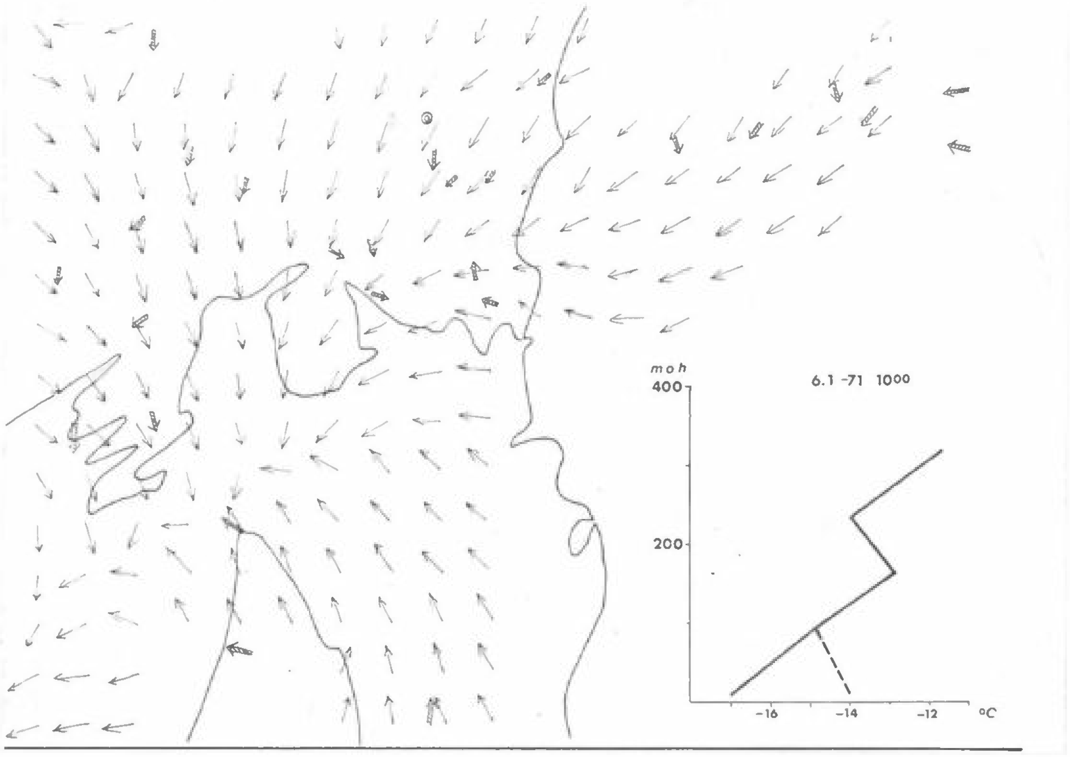

Fig. 9

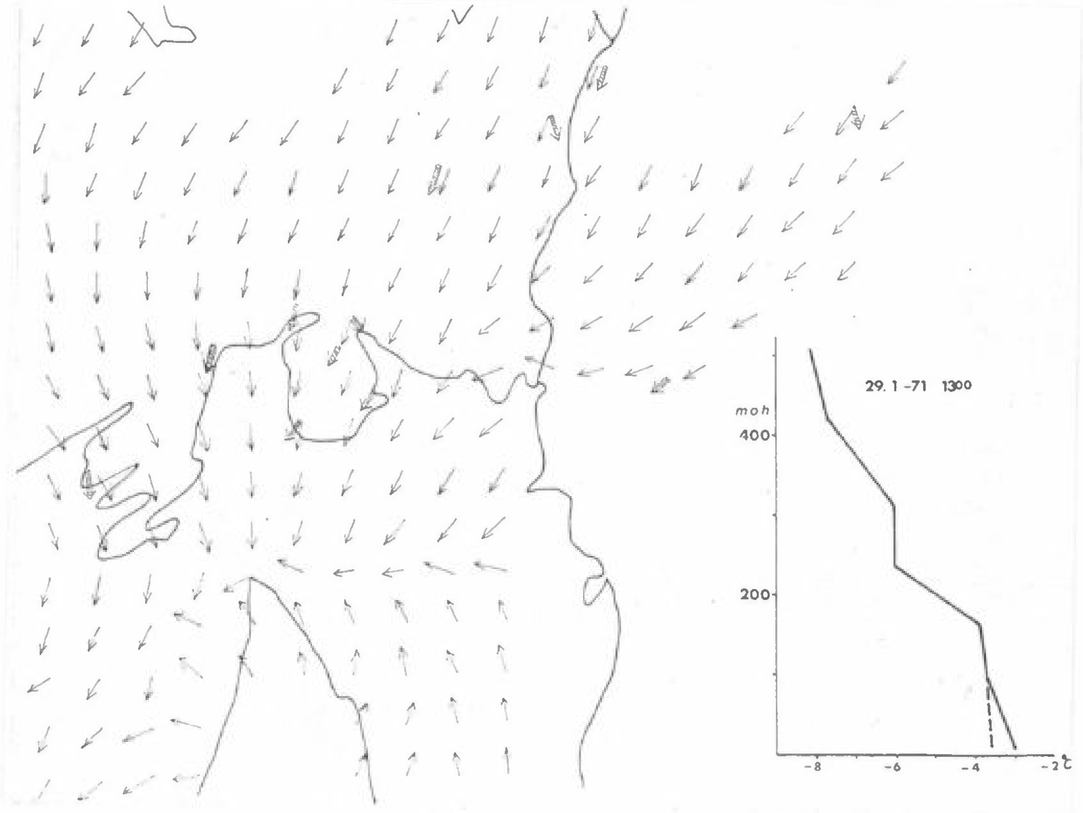

Fig. 10

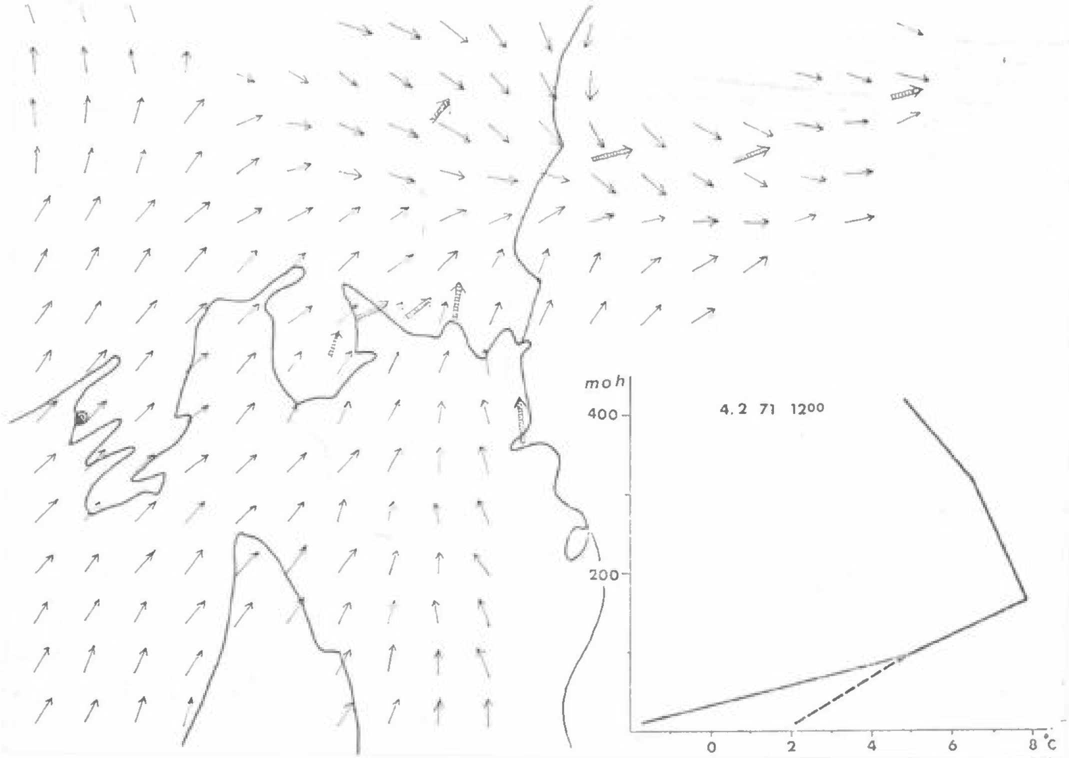

Fig. 11

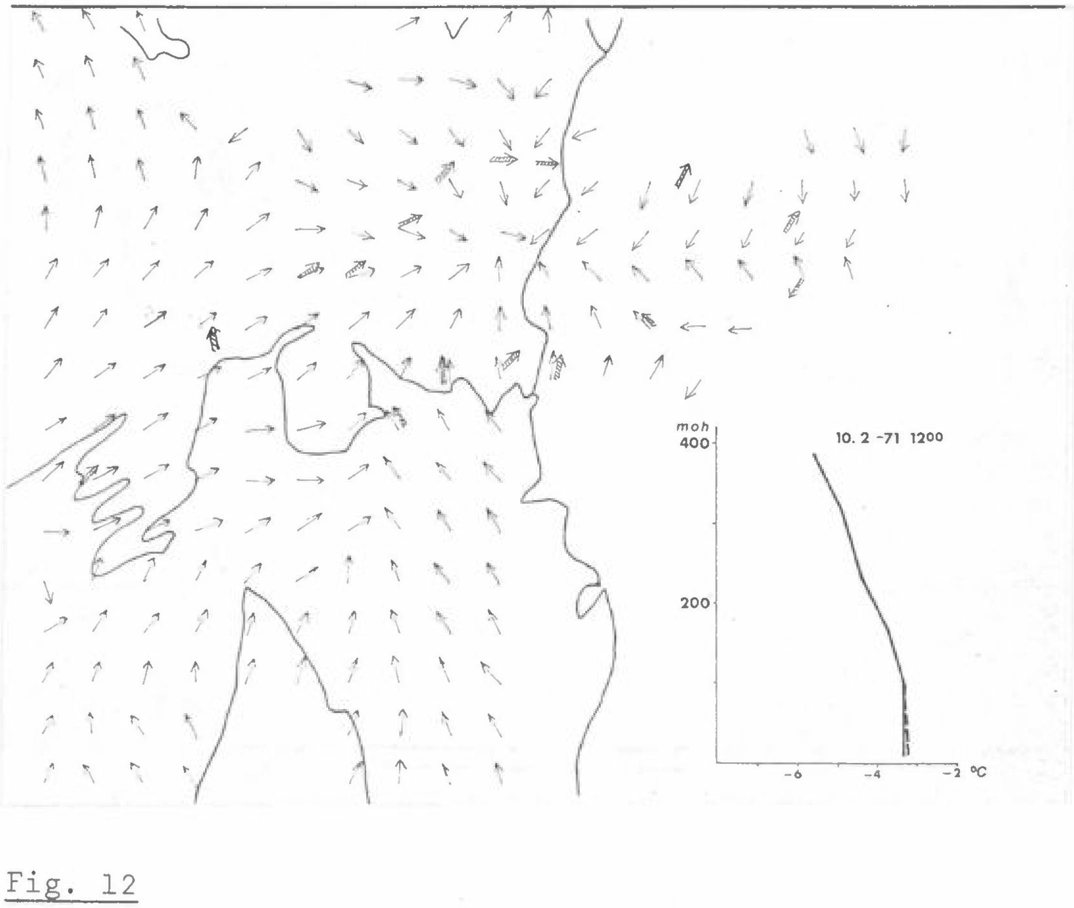

Fig. 12

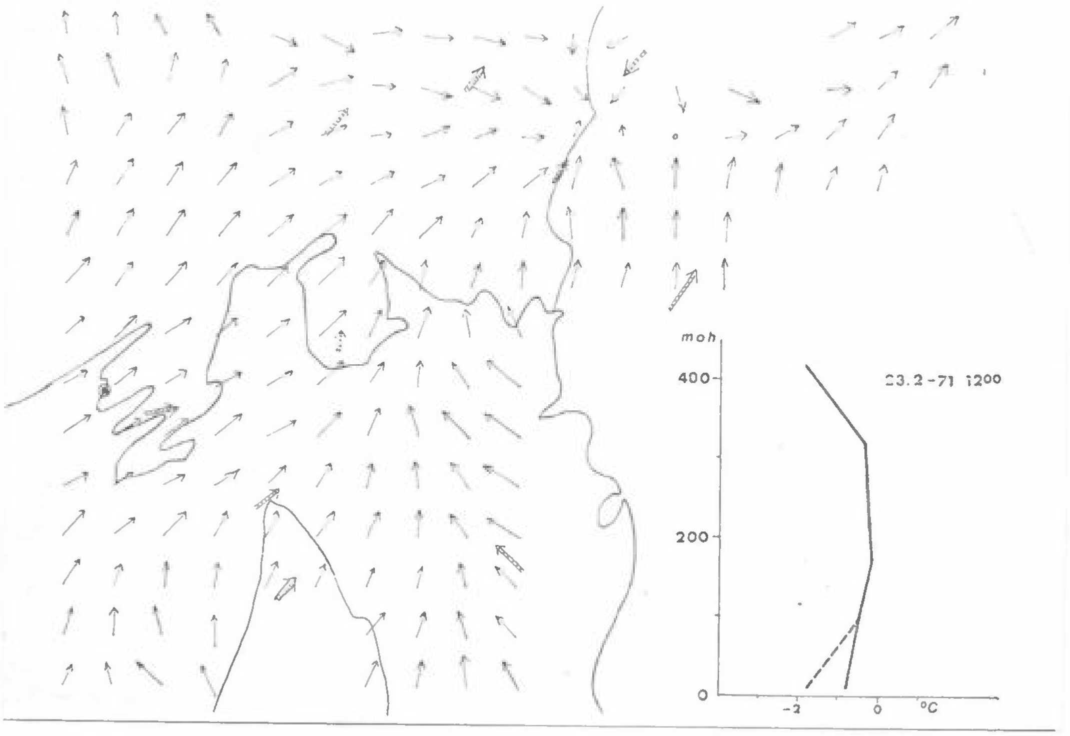
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Fig. 13

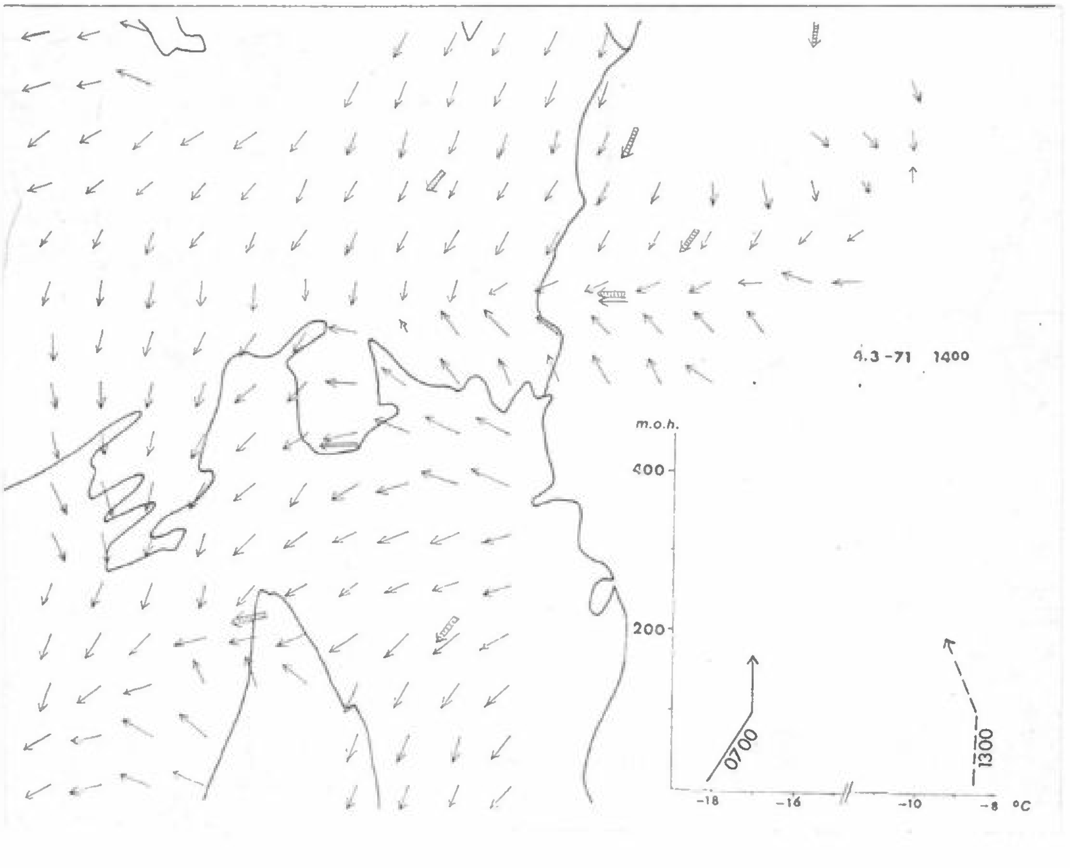
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Fig. 14

Case study 10: 2 p.m., 4th March 1971 (Fig 14)

The vertical temperature stratification is moderately stable. The general wind field comes from north-east and no stagnation point is neither observed nor calculated. The observed and calculated wind directions match well.

Case study 11: 1 p.m. 5th March 1971 (Fig 15)

This is a typical wind field in air pollution situations in Oslo. The air flows down the valleys and out of the Oslo-fjord. The wind blows northward in the south-eastern part. The stagnation point is observed over the centre of the city, close to the convergence zone. The calculated and observed winds match well.

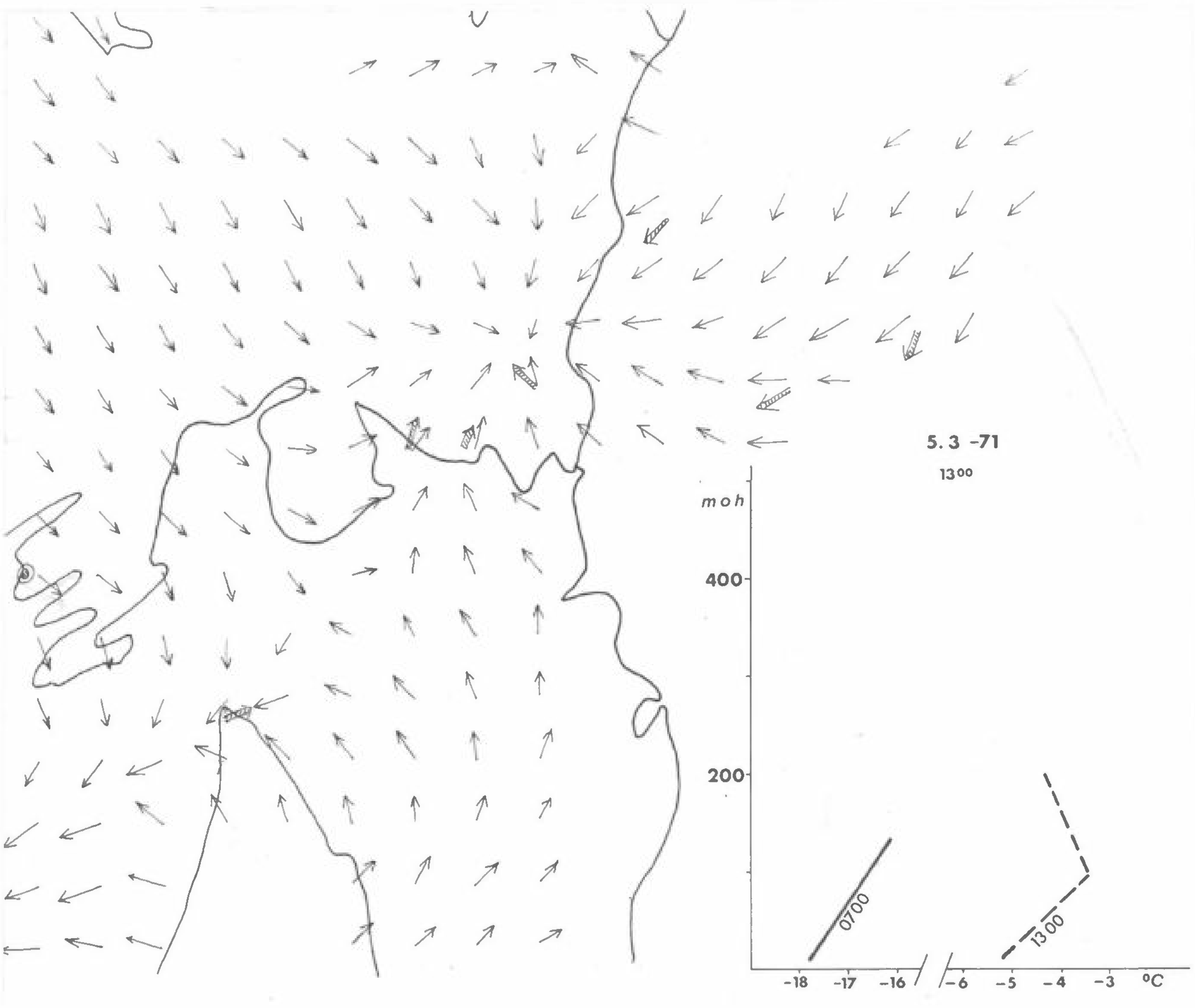

Fig. 15

Summary of the case studies

In some case studies (1, 5, 6 and 7), the presented wind model does not work well in some regions of Oslo. This may be due to local canalization of the air flow which is not resolved in the model, or to wind fluctuations which the semi-stationary wind model does not take into account. Besides, the wind model is sensitive to the measurements from the key observing stations in the valleys. Some discrepancies are evidently due to measurements from these stations that are not representative for their region (4 and 7).

The existence and the location of a stagnation point over the urbar area of Oslo is reflected in our model calculations. The main features of the air streams round the Oslo fjord are also reflected in the different case studies.

This indicates that our approximation of the convergent wind field work fairly well and that the resulting vertical velocity may be regarded as a first approximation on the scale that is resolved in our grid system.

5 CALCULATION OF THE CONCENTRATION OF SULPHUR DIOXIDE

The daily emission of SO_2 was estimated from the mean seasonal delivery of sulphur in oil by using the daily degree-day number and the seasonal sum of these numbers. The degree-day number denotes how many degrees centigrade the daily mean temperature is below 17°C. The hourly emission was estimated from the daily emission fluctuations used by Halpern, Simon and Randell in their study in New York (10).

The sinkterm of SO_2 (A) was assumed to be a function of the SO_2 concentration in the following way:

$$A = cq + dq^2$$

$c = 1.0 \cdot 10^{-6}\ s^{-1}$

$d = 0.25\ s^{-1}\ (g/m^3)^{-1}$

The functional form of A and the values c and d are estimated by J. Nordø in connection with modelling long range transport of air pollutants.

The wind model was used together with the presented estimates of the sources and sinks for SO_2 in the region, and the SO_2 concentration was calculated in all the grid points during the 4 days: 17th-18th Dec./1970, 3rd-4th Jan./1971, 4th-5th Jan./1971 and 5th-6th Jan./1971.

The timing of the daily measurements was the reason for chosing the calculation interval from 2 p.m. to 2 p.m. the next day. The initial value of SO_2 concentration was chosen to be zero. This approximation will influence the calculations during the first few hours. There was not found any reason to improve this approximation although it could easily be done, as for example, by using the steady state solution for the given wind field as an initial value.

The hourly mean SO_2 concentration measured at four stations was compared with the calculated values at the grid point within the same square kilometer.

Two of the stations, St Olavs-Plass and St Hanshaugen were in the centre of the city (Fig.1). The difference in height between these stations was about 70 m. It did not seem that this difference made any deviation in concentration. This supports our assumption of mixing in the lowest layer. The two other stations were placed south (Bygdöy) and north (Kjelsås) of the city centre.

The Fig. 16 shows the calculated and observed values at the four stations from 3 p.m. the 17th December to 2 p.m. the 18th Dec. During the night, the windspeed slowed down from about 5 meter per second to an irregular wind of about 1 meter per second. This is the reason for the increase of the SO_2 concentration that is observed and calculated.

The calculated increase at St Olavs-Plass is too low compared to the observed values. It is possible that an investigation of such discrepancies might be used to improve the model, but no acceptable explanations have been found. An increase from about 100 µg SO_2/m^3 to about 300 µg SO_2/m^3 at St. Hanshaugen and an increase from about 30 µg SO_2/m to 100 µg SO_2/m^3 at Bygdöy compared well. The calculations at Kjelsås do not show any large change, and the measurements do not show any fluctuation at all. The reason for this may be the limited sensitivity of the instrument used.

From the presented calculations, it may be concluded that the response of the SO_2 concentration of larger changes in wind velocity is correct with respect to time and space. This indicates that the emission of SO_2 and the wind field are taken into consideration as a fair approximation.

In Fig. 17, the calculated and observed concentrations between the third and forth of January are shown. All over the area, the calculated SO_2 concentrations are somewhat too high. On the other hand, the calculated fluctuations of some hours duration are largely observed in the same manner at the stations St Olavs-Plass, St. Hanshaugen and Bygdöy. One exception is a three hour increase between 1 and 3 a.m. at St. Hanshaugen. This increase is observed somewhat later and with smaller amplitude at St. Hanshaugen. The reason for this might be a local increase of the emission which is not considered in the calculation.

The short term fluctuations in the calculated SO_2 concentrations are mainly due to changes in the wind field. These fluctuations are not easily recognised when the wind at one of the wind stations is studied. The total ventilating effect resulting from the air flow in several valleys has to be considered. It may therefore be concluded that one wind station is not enough to describe actual short term fluctuations of the air pollution concentration in Oslo. Further, it indicates that small fluctuations in the wind field over the centre of Oslo are fairly well reflected by the net of wind measuring stations placed in the valleys (V_1, V_2, V_3, V_4).

The Fig. 18 shows the measured and calculated values between the 4th and 5th January. The largest deviations occur during the day when the calculated values are much to high.

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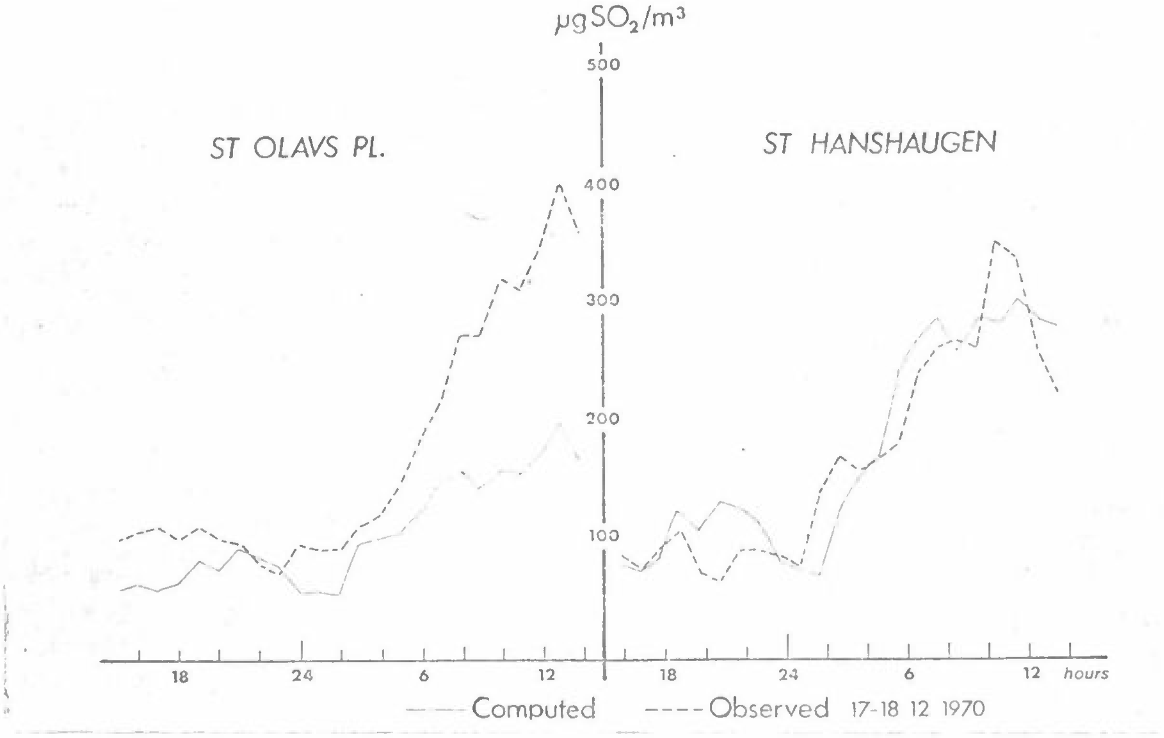

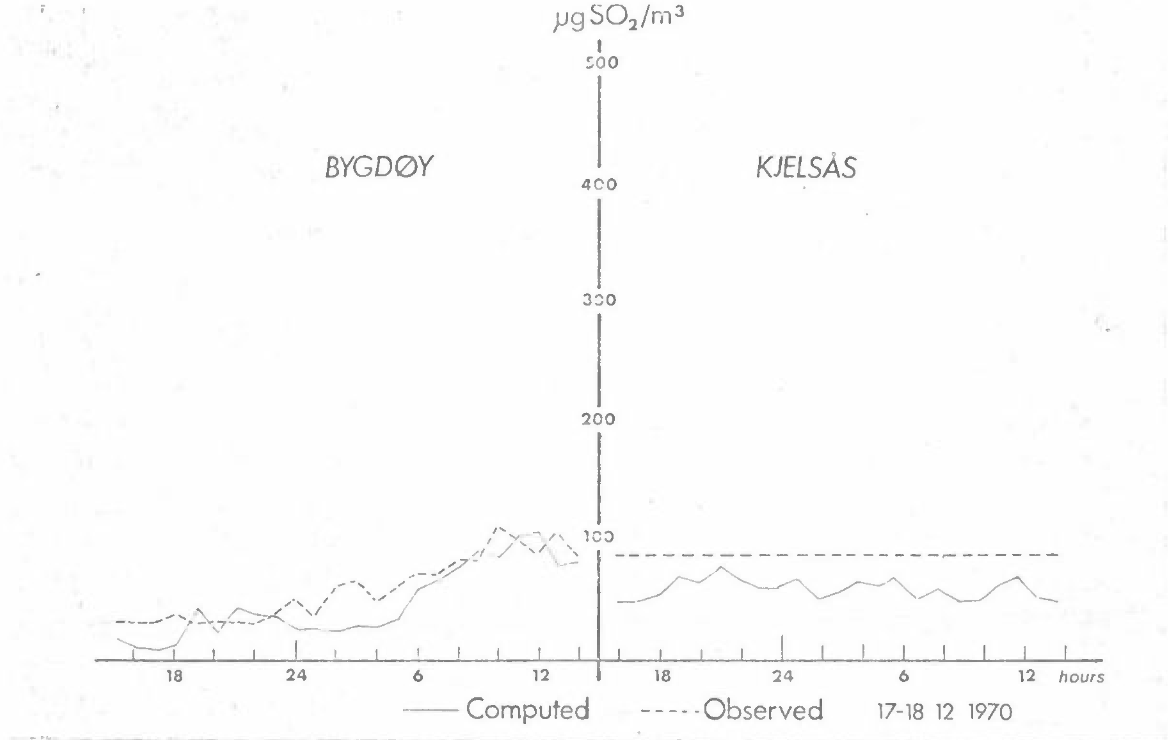

Fig. 16

A similar tendency is found on the 6th January. These results are shown in Fig. 19. The calculated and observed values do not match well in the centre of the city. It may be recalled from case study 5 (Fig. 9), that the observed and calculated wind field do not match well either. On the other hand, the fluctuations at Bygdöy match fairly well. The SO_2 concentration at Bygdöy is mainly due to transportation from the centre of Oslo. This means that this transport is fairly well taken into account. The observed values at St. Hanshaugen is specially low this day.

The correlation coefficient between the hourly calculated and observed SO_2 concentrations from the four stations during the four days turned out to be 0.75. This means that much of the variations remain to be explained. On the other hand, many of the calculated short term fluctuations may be recognised in the observations at several stations. In particular, the fluctuations at Bygdöy (Fig. 19), should be noted when this station is down wind of the centre of Oslo. The resemblance in the short term fluctuations shows that ventilation of SO_2 in Oslo is taken into consideration in a fairly realistic way. The difference between the calculated and observed values has been correlated with other meteorological parameters and it turns out that the correlation between this difference on one hand and temperature and humidity on the other hand,is about 0.80 on all stations. This indicates that more sophisticated chemical processes should be considered when trying to improve the model.

The dust on the daily exposed filters in Oslo has been analysed with respect to sulphur. The sulphur content on the filters appeared to be closely connected to the measured SO_2 concentration, the temperature and the humidity in the air.

If the applied sink-term for SO_2 is regarded as a source for particulate sulphur, the computed concentrations were of the same order of magnitude as the referred measurements.

6 CONCLUSION

This work is a first attempt to consider systematic vertical motion and unhomogeneous horizontal motion in modeling air pollution near the ground.

In Oslo, the presented wind model worked fairly well in 11 case studies during winter time and gave a reasonable wind estimate even during periods with weak wind conditions that are often observed in Oslo.

Although only about half of the short term variance in the measured SO_2 concentration is explained, it may be concluded that the ventilation is taken into consideration in an approximatively correct way. To show the relative importance of the different removal processes of SO_2 from the ground level in Oslo, the different terms of equation (2) were integrated over the Oslo region, and the results are given in percent of the SO_2 emission:

- removal by vertical transport:	40 - 80 %
- " by horizontal transport:	0 - 50 %
- " by the applied sinkterm:	5 - 20 %

Due to the organized vertical lifting of the air over Oslo, the SO_2 pollution within the city remains tolerable, despite the high frequency of stagnating periods during winter.

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