

Estimates of sources of air pollution in Christchurch compared with recorded concentrations.

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Abstract

In the 1998 "Christchurch inventory of total emissions" the mass of air pollutants emitted into the air during the course of a 'typical winter's day' from traffic, industry and home heating were estimated. These estimates have been used as the basis for deriving regulations to reduce the amounts of health-damaging pollutants in the air we breathe. In this paper the estimates of the amounts of three of these pollutants, fine particles with an aerodynamic diameter less than 10 microns (PM₁₀), carbon monoxide (CO), and oxides of nitrogen NO and NO₂ (NOx), are compared with the concentrations recorded at the St Albans Air Quality Monitoring Station. Calculations using a model of the distribution of PM₁₀ in the air and these inventory estimates gave good agreement between recorded and calculated concentrations. From this agreement it has been claimed that the model validates the inventory estimates. Using the same model and the estimates of emissions of NOx and CO from the inventory, the recorded concentrations of these were from four to six times higher than the calculated concentrations. The inventory estimated that almost equal amounts of PM₁₀ and NOx were emitted during winter evenings. The concentration of NOx recorded in the air was regularly four to five times higher than the concentration of PM₁₀. Similarly, the inventory estimated that ten times more CO than PM₁₀ was emitted. However, the concentration of CO in the air was almost 60 times the concentration of PM₁₀. These results call into question the claim that the model with its several assumptions validates the estimates of emissions contained in the inventory. It is asked whether these estimates are shown to be a sound basis for forming policies with very considerable health, social and economic consequences.

Introduction

Air pollution is claimed to pose a considerable health hazard in New Zealand, and particularly in Christchurch, where concentrations of fine particles with an

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aerodynamic diameter of less than 10 microns (PM_{10}) are said to sometimes equal those in the most polluted cities in the world (Woodward *et al* 2002). It has been variously estimated that increased annual mortality attributable to PM_{10} may be as high as 20 to 30 (Foster 1996), or 70 (Wilton 1999), or 181 (Fisher *et al* 2002), or 158 (Fisher *et al* 2005). PM_{10} has also been claimed to cause considerable sickness, resulting in 300,000 to 600,000 “reduced activity days” annually (Wilton 2001), and an increase of 4% to 5% in hospital admissions for respiratory complaints (McGowan *et al* 2002). High concentrations of PM_{10} and other pollutants typically accumulate on still, winter evenings. Principally for these reasons, it is considered important to know the sources and times of emissions of the pollutants so that regulations, such as those in the Environment Canterbury Air Plan which will severely reduce the use of the popular solid-fuel heaters in the city, may be introduced to mitigate the ill effects.

The “Christchurch inventory of total emissions” (Fisher *et al* 1998), provides estimates of the masses of several pollutants which are emitted from industry, traffic and home-heating during the course of a “typical winter’s day” in Christchurch. The inventory was compiled using the “Bottom up” approach (Kuschel & Kingsland 1998). Wood and coal burned on open fires or in a variety of stoves is used to heat over forty percent of the houses in the city. These were estimated to produce over ninety percent of the winter time emissions of PM_{10} . These estimates were derived from a telephone survey, when responding householders were asked how many logs of wood or buckets of coal they burned on open fires or several categories of stoves during the course of a typical winters day. The reported quantities of fuel were multiplied by fuel factors and appliance factors to give the estimates of the amounts of pollutants emitted during the course of the day.

Motor vehicle emission factors were developed from a survey of international studies. From these, and from Canterbury Regional Council data on traffic in the city, the emissions from traffic during the day were estimated.

The inventory estimated that between 4 pm and 10 pm on winter evenings when the greatest concentrations of pollutants occur, 4,255 kg of PM₁₀, 42,768 kg of CO, and 3,983 kg of NO_x were emitted into the air over the 6,016 ha of the inner city suburbs. About 90% of the PM₁₀ was estimated to come from home heating, about ninety percent of the NO_x from motor traffic, and about half the CO from each source. Two subsequent inventories using similar methods of estimation have given similar results (Wilton 2001a, Scott & Gunatilaka 2003). Giving preliminary results from a receptor model, Senaratne *et al* estimated that 29% of the PM₁₀ came from home heating, 30% from traffic, 20% from sea spray and 21% from suspended road dust, which may have included some re-cycled home-heating emissions.

Using a model of the way pollutants are distributed in the air after they are emitted, and the estimates of the emissions from the inventory, Gimson & Fisher (1997) calculated the hourly concentrations of PM₁₀ to be expected on the seventeen days with the highest recorded concentrations between 1988 and 1995. The calculated average daily concentrations were 1.01 of the observed concentrations, varying from 0.82 to 1.47. It has been claimed that this close agreement indicates the accuracy of the estimates from the inventory (Fisher 1999), and they have been accepted as such in subsequent calculations of reductions in pollution to be expected from a variety of interventions.

In this paper the same model and assumptions have been used, as have the inventory estimates of emissions of CO and NO_x to calculate the concentrations of CO and NO_x to be expected on these seventeen nights, and they have been compared with the concentrations recorded at the air quality monitoring station. Meteorological data, and recorded and calculated concentrations of pollutants for one typical night (16 6 90) are shown in detail in Table 1 and Table 2. This night was one of two chosen by Gimson and Fisher as examples to illustrate their model.

Temperatures at one metre and ten metres above the ground, wind speed, and concentrations of PM₁₀ (Beta gauge $\mu\text{g}/\text{m}^3$), CO (mg/m^3) and NO_x ($\mu\text{g}/\text{m}^3$)

three metres above the ground as measured at the St Albans Air Quality Monitoring Station from 4 pm to 11 pm are given in Table 1. NO_x is composed of NO and NO₂. In winter evenings in Christchurch the monitoring station records show that NO₂ makes up from about 4% to 10% of the mass of the two gases. Jiang *et al* (2005) also found that when concentrations of NO increased the concentrations of NO₂ did not continue to increase.

The concentrations of NO and NO₂ are recorded as $\mu\text{g}/\text{m}^3$. The concentration of NO_x is recorded as ppb. The concentration of NO_x in $\mu\text{g}/\text{m}^3$ can be calculated by multiplying the concentration of NO in $\mu\text{g}/\text{m}^3$ by 1.53 (46/30, the molecular weight of NO₂/molecular weight of NO) and adding this to the concentration of NO₂, or more simply by multiplying NO_x ppb by 2.05.

Time pm	CO	PM ₁₀	NO _x	Wind m/s	Temperature °C @		
	mg/m ³	$\mu\text{g}/\text{m}^3$ *	$\mu\text{g}/\text{m}^3$ **		1 metre	10 metre	Difference
4	1	18	122	1	17.6	14.8	2.8
5	6	30	685	0.6	10.8	12.6	-1.8
6	15	151	1431	0.5	6.9	10.7	-3.8
7	17	250	1495	0.8	5.7	10	-4.3
8	19	334	1617	0.5	4.9	8.9	-3.9
9	17	392	1430	0.7	5.2	8.7	-3.5
10	18	284	1563	0.6	4.4	8.5	-4.1
11	22	331	1856	0.3	3.1	7.9	-4.8

Table 1. A typical winter evening. Measurements from St. Albans air quality monitoring station Christchurch, 16 June 1990. (Records supplied by Canterbury Regional Council). * Beta gauge, ** ppb x 2.05.

On typical high-pollution winter days, by the afternoon there is a moderate breeze, and it is warmer near the ground than at 10 metres. Pollutants are advected and ascend after emission. They do not accumulate near the ground, where concentrations are relatively low. At sunset the wind drops. The air near the ground is cooler than the higher air. Emitted pollutants are not advected, nor do they become mixed significantly with the warmer air above and they become concentrated in the lower, cooler air. The height to which they ascend, known as the mixing height, is related to the intensity and altitude of the tem-

perature inversion (Gimson 1999). Table 1 shows the marked temperature inversion which typically develops down to or below 10 metres altitude. It shows that the high night-time concentrations of PM₁₀, CO and NO_x have not accumulated from earlier emissions, but have been emitted during the evening itself. In the model it is assumed that the rate at which pollutants are advected is directly related to the wind speed, and that the pollutants are evenly and rapidly distributed from the ground surface up to the mixing height inversion. It is assumed that the mixing height varies from 500 metres during the day, to 100 metres from 5pm to 8pm, to 70 metres from 8pm to 10pm, to a minimum height of 25 metres from then until 6am. The concentration to be expected at any hour during the course of the day is calculated from the initial concentration, the wind speed, the estimated emissions from the inventory, and the assumed mixing height. The initial concentration was set at zero at 2pm, which is consistent with the data. The wind speed is from measurements at the monitoring station. The estimated emission is the variable which is said to be verified. The mixing height is an assumed, not a measured variable. It determines the height, and so the volume of air in which the pollutants are confined, and so their concentration in the air. Gimson and Fisher say a realistic choice was made for this, **“which can only be judged by the comparison of modelled concentrations with observations”** (my emphasis). A minimum mixing height of 25 metres was assumed. The assumption of the uniform distribution of PM₁₀ up to this mixing height was not verified by measurement.

Using the same assumptions about the mixing height, and the inventory estimates of emissions of 707g of PM₁₀, 662g of NO_x and 7,109g of CO per hectare from sources in the inner suburb area where the monitoring station is located, I have similarly calculated the concentrations of PM₁₀, NO_x and CO which would be expected to accumulate during the course of the evening. These expected concentrations of the three pollutants, and the recorded concentrations for the night of 16 6 1990 are given in Table 2.

Recorded and calculated concentrations of PM₁₀ were close on this and all the 17 high pollution nights chosen by Gimson and Fisher to test the model. The

recorded concentrations of NO_x and CO were very different from the modelled concentrations. Recorded concentrations of NO_x were three to five times higher than the modelled concentrations, and recorded concentrations of CO were four to eight times higher. Mean hourly concentrations of the three pollutants recorded between 5pm and 11pm on all the 17 nights are listed in Table 3, along with the emissions estimated in the inventory.

Time pm	PM10 ($\mu\text{g}/\text{m}^3$)			NO _x ($\mu\text{g}/\text{m}^3$)		CO (mg/m^3)	
	1	2	3	2	3	2	3
4			18		125		1
5	150	140	30	180	690	1	6
6	230	230	151	260	1,430	2	15
7	290	280	250	280	1,500	2	17
8	400	390	334	380	1,620	3	19
9	440	440	392	430	1,430	4	17
10	400	390	284	380	1,570	3	18
11	400	400	331	390	1,860	4	22

Table 2. Calculated (columns headed 1 and 2) and recorded (column headed 3) concentrations of PM10, NO_x and CO in Christchurch, 16 June 1990. Column 1 calculated by Gimson and Fisher 1997, using their model and inventory inputs. Column 2 calculated by author, using the model of Gimson and Fisher, and inventory inputs. Column 3 recorded at St.Albans air quality monitoring station (data supplied by Canterbury Regional Council).

From each hectare in the inner suburbs 707g of PM₁₀ were estimated to be emitted into the air between 4pm and 10pm, and slightly less, 662g, of NO_x. The mean concentration of NO_x recorded in the air was 4.6 times higher than the mean concentration of PM₁₀. Ten times more CO than PM₁₀ was estimated to be emitted into the air. The mean concentration of CO recorded in the air was almost sixty times greater than the mean concentration of PM₁₀.

Discussion

From the good agreement between the calculated and recorded concentrations of PM₁₀, as evident in Table 2, it has been claimed that “this powerful result provides an indication of the accuracy of the inputs – especially the emissions derived from the emissions inventory” (Fisher 1999). However, it is also evident from Table 2 that using the inventory estimates of emissions of NO_x and CO, and assuming that these ascend and are uniformly distributed to the same mixing height as the PM₁₀ emissions, the concentrations of these pollutants recorded in the air are several times greater than the calculated concentrations. The recorded concentrations would be calculated to result from emissions of CO and NO_x, from traffic or from other sources, four to six times greater than estimated in the inventory.

If the mixing heights were one fifth those used in the model, the modelled hourly concentrations of NO_x and CO would have been close to the recorded concentrations. But then the recorded concentrations of PM₁₀ would have been attributable to emissions one fifth of those given in the inventory. Table 3 shows that the relative amounts of the three pollutants estimated to have been emitted in the inventory do not agree with the recorded concentrations. In the inventory it was estimated that the amount of NO_x emitted during the evening hours was slightly less than the amount of PM₁₀. Four to five times as much was recorded in the air. Similarly, about ten times as much CO was estimated to have been emitted. Fifty eight times as much was recorded. Fisher *et al* (2005) found that concentrations of CO on winter nights were about 45 times greater than the concentrations of PM₁₀. They did not compare these ratios with the inventory estimates.

If the emissions of NO_x and CO were about five times greater than those estimated in the inventory, then the concentrations calculated in Table 2 using the model would have been close to the recorded concentrations, and the ratios of estimated emissions to recorded concentrations would have been similar for all three pollutants.

The mixing height is a crucial variable in the model. It is not clear how Gimson and Fisher derived the values for this variable. Gimson and Fisher (1997) made a realistic choice, which they judged by comparing modelled concentrations with observations. From wind speed and temperatures measured at 3 m and 21 m above ground Gimson (1999) estimated mixing heights lower than 10 m during the winter of 1995, and found that the modelled and observed hourly and daily concentrations rose and fell together.

In calculating the concentrations of NO_x and CO expected hourly which are given in Table 2, it was assumed that the mixing heights were the same for NO_x and CO as given for PM₁₀ (but see below). When these mixing heights were used with the inventory emissions, the concentrations of NO_x recorded were four to five times greater than the calculated concentrations, and the recorded concentrations of CO about six times greater. If the three pollutants are evenly distributed up to the same mixing height, whatever it may be, the concentrations of each recorded in the air would be expected to be in proportion to the amounts of each emitted. Almost equal quantities of NO_x and PM₁₀ were estimated to be emitted (94/100). Four to five times as much NO_x was recorded. Similarly, about ten times more CO than PM₁₀ was estimated to be emitted. Almost 60 times as much was recorded. The results cast serious doubts on the estimates in the inventory, or on the model which has been claimed to validate them. It could be concluded that the box model does not validate the estimates in the inventory. It may invalidate them.

The good fit between the calculated and recorded concentrations of PM₁₀ does not validate the inventory estimates. It may have resulted from the good inventory estimates, or from the appropriately chosen mixing heights used in the model. It is not at all clear that the mixing heights were chosen independently from this anticipated result. Likewise, the poor fit between the calculated and recorded concentrations of CO and NO_x may not result from poor estimates of these emissions, but from the use of inappropriate mixing heights in the model.

If the emissions are not evenly distributed up to the assumed mixing heights, but are stratified in the air, the samples taken at three metres at the monitoring station may not be a good sample of the polluted air above the city. The height to which pollutants ascend may vary not only with meteorological conditions, as assumed by Gimson (1999), but also with the altitude, temperature, velocity and direction at which they are emitted.

Ninety two percent of the PM_{10} is estimated to come from domestic heating, and is discharged vertically from a minimum height of 3 metres. Half the CO is estimated to come from the same source. Eighty seven percent of the NO_x , and half the CO, are estimated to come from motor vehicles, so are largely emitted horizontally a few centimetres above the ground. They may not rise as high as the PM_{10} , so may be over-represented in the air sampled at three metres, while the PM_{10} may be under-represented. Reisinger *et al* (1998) compared inventory estimates of CO/ NO_x ratios with measured ratios in Christchurch in 1997, and found a two-fold to three-fold difference. They concluded that the discrepancy probably resulted from assumptions made in applying the inventory, with different mixing heights and non-uniform mixing as contributing causes.

Monitoring data on stratification of pollutants in the air near the ground in Christchurch are not available. The monitoring height of 3 metres was presumably chosen to give a sample of the air we breathe, not to give a sample of the pollutants emitted into the air over the city.

However, the agreement between the estimated emissions of PM_{10} and the recorded concentrations which was calculated using the assumed mixing heights and other model assumptions has been emphasised. It has been claimed to indicate the accuracy of the estimates from the inventory and accepted as such (Fisher 1999).

The large discrepancies between estimates of emissions of other pollutants and the recorded concentrations have been ignored. It has been accepted that

estimates of emissions will in general never agree with records, so that more complex and dynamic models must be used, and should take precedence over measurements (Fisher 1999).

If this is so, and discrepancies such as those shown here are indeed usual, serious doubts are cast on the reliability of the estimates from these sorts of inventories for quantifying the sources of emissions into the air which is monitored in Christchurch, which is the air we breathe. Despite these uncertainties about the inventory estimates, they have been accepted as the basis of regulations which would greatly restrict and reduce the use of solid fuel heaters which are used to heat 40% to 50% of the houses in the city.

Conclusions

There are very large differences between the inventory estimates of the amounts of major pollutants emitted into the Christchurch air and the concentrations of those pollutants recorded in the air. Recorded concentrations of NO_x and CO were several times higher than those calculated from the estimates using the model (Gimson and Fisher 1997) which was claimed to validate the estimates.

These discrepancies suggest that the inventory estimates may not be reliable, or that the model which is claimed to validate them is inadequate. However, they have not been explained, but have been ignored. The inventory estimates of sources of emissions have not been shown to be reliable. They may not be a reliable basis formulating policies for improving air quality.

Acknowledgements

I wish to thank the Canterbury Regional Council and staff for supplying large numbers of air quality monitoring records, and for advice on their interpretation.

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Submitted to Weather and Climate , August 2006. Revised, January 2007