Inter-comparison of Gaussian Air Dispersion Models for Regulatory Applications in Hong Kong

by

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A Thesis Submitted to
The Hong Kong University of Science and Technology
in Partial Fulfilment of the Requirements for
the Degree of Master of Philosophy
in Atmospheric, Marine and Coastal Environmental (AMCE) Program

August 2008, Hong Kong
Authorization

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by

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This is to certify that I have examined above MPhil Thesis and have found that it is complete and satisfactory in all respects, and that any and all revisions required by the thesis examination committee have been made.

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# Table of Contents

Inter-comparison of Gaussian Air Dispersion Models for Regulatory Applications in Hong Kong  
Authorization  
Inter-comparison of Gaussian Air Dispersion Models for Regulatory Applications in Hong Kong  
Acknowledgements  
Table of Contents  
List of Figures  
List of Tables  
Abstract  

<table>
<thead>
<tr>
<th>Chapter 1</th>
<th>Introduction</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Background</td>
<td>12</td>
</tr>
<tr>
<td>1.2</td>
<td>Situation in Hong Kong</td>
<td>13</td>
</tr>
<tr>
<td>1.3</td>
<td>Scope of the study</td>
<td>14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 2</th>
<th>Gaussian Air Dispersion Models</th>
<th>17</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Gaussian Plume Dispersion Equation</td>
<td>18</td>
</tr>
<tr>
<td>2.2</td>
<td>Boundary Layer Parameters</td>
<td>20</td>
</tr>
<tr>
<td>2.2.1</td>
<td>Mixing Height</td>
<td>21</td>
</tr>
<tr>
<td>2.2.2</td>
<td>Pasquill-Gifford Stability</td>
<td>21</td>
</tr>
<tr>
<td>2.2.3</td>
<td>Monin-Obukhov Similarity Theory</td>
<td>23</td>
</tr>
<tr>
<td>2.3</td>
<td>The Four Models</td>
<td>25</td>
</tr>
<tr>
<td>2.3.1</td>
<td>Conventional Models</td>
<td>25</td>
</tr>
<tr>
<td>2.3.2</td>
<td>Advance Models</td>
<td>27</td>
</tr>
<tr>
<td>2.4</td>
<td>Literature Review</td>
<td>31</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 3</th>
<th>Case Studies</th>
<th>34</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Hong Kong International Airport</td>
<td>35</td>
</tr>
<tr>
<td>3.1.1</td>
<td>Background</td>
<td>35</td>
</tr>
<tr>
<td>3.1.2</td>
<td>Case Setup</td>
<td>36</td>
</tr>
<tr>
<td>3.1.3</td>
<td>Results</td>
<td>46</td>
</tr>
<tr>
<td>3.2</td>
<td>Castle Peak Power Station</td>
<td>57</td>
</tr>
<tr>
<td>3.2.1</td>
<td>Background</td>
<td>57</td>
</tr>
<tr>
<td>3.2.2</td>
<td>Case Setup</td>
<td>58</td>
</tr>
<tr>
<td>3.2.3</td>
<td>Modelling Results</td>
<td>62</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 4</th>
<th>Discussion</th>
<th>73</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Performance discrepancies and their causes</td>
<td>74</td>
</tr>
<tr>
<td>4.1.1</td>
<td>Disappearing Plumes in ISC and AUSPLUME</td>
<td>75</td>
</tr>
<tr>
<td>4.1.2</td>
<td>Nighttime Concentration Peaks in AERMOD</td>
<td>79</td>
</tr>
<tr>
<td>4.1.3</td>
<td>Low wind condition in ADMS</td>
<td>83</td>
</tr>
<tr>
<td>4.1.4</td>
<td>Difference in Mixing Height Predictions</td>
<td>84</td>
</tr>
<tr>
<td>4.1.5</td>
<td>Conventional vs. Advance models</td>
<td>89</td>
</tr>
</tbody>
</table>
List of Figures

Figure 1 Instantaneous and corresponding ensemble averaged plume (Lakes Environmental) ................................................................. 18
Figure 2 Pasquill-Gifford stability classes and classification scheme .......... 22
Figure 3 Variation of $\sigma_y$ and $\sigma_z$ with downwind distance for the six Pasquill-Gifford stability classes ......................................................... 23
Figure 4 Dimensional Representation of variation of Monin-Obukhov length with atmospheric stability (manual of ADMS-Urban version 1.6, CERC, 2001) .................................................................................. 24
Figure 5 Schematic flow of Old generation Gaussian air dispersion models .... 26
Figure 6 Schematic flow of advance Gaussian air dispersion models .......... 28
Figure 7 GIS map showing the Airport setup .................................................. 37
Figure 8 Three-dimensional view of emission sources in the Airport .......... 38
Figure 9 Emission profile of Idle planes and APU in 2003 .......................... 40
Figure 10 Emission profile of takeoff and climbout in the direction of 25L in 2003 .................................................................................... 40
Figure 11 Emission profile of takeoff and climbout in the direction of 07R in 2003 .................................................................................... 40
Figure 12 Emission profile of takeoff and climbout in the direction of 25R in 2003 .................................................................................... 41
Figure 13 Emission profile of takeoff and climbout in the direction of 07L in 2003 .................................................................................... 41
Figure 14 Emission profile of approach along 07L ........................................ 41
Figure 15 Emission profile of approach along 07R ........................................ 42
Figure 16 Emission profile of approach along 25L ........................................ 42
Figure 17 Emission profile of approach along 25R ........................................ 42
Figure 18 Wind Roses at the Airport in January and July 2003 .................... 44
Figure 19 Mean Contour in January and July 2003 at Airport ...................... 47
Figure 20 100th percentile contours in January and July 2003 at Airport .... 48
Figure 21 99th percentile contour in January and July 2003 at Airport .......... 49
Figure 22 98$^{th}$ percentile contour in January and July 2003 at Airport ...... 50
Figure 23 Time series of NO$_x$ concentration in January and July 2003 at Tung Chung by models ................................................................. 54
Figure 24 Time series of NO$_x$ concentration at Tung Chung in January and July 2003 with the observation ...................................................... 55
Figure 25 GIS map showing the Power Plant setup ...................................... 58
Figure 26 Hourly emission factor profile of the Power Plant ...................... 59
Figure 27 Wind Roses at the Power Plant in January, April, July and October 2004 .......................................................... 61
Figure 28 Monthly mean contours in January and April 2004 at Castle Peak ... 64
Figure 29 Monthly mean hourly contours in July and October 2004 at Castle
Figure 59 Day 206 hour 3 & 4 at the Power Plant ................................................... 117
Figure 60 Day 206 hour 5 & 6 at the Power Plant ................................................... 118
Figure 61 Day 206 hour 7 & 8 at the Power Plant ................................................... 119
Figure 62 Day 206 hour 9 & 10 at the Power Plant .................................................. 120
Figure 63 Day 206 hour 11 & 12 at the Power Plant ............................................... 121
Figure 64 Day 206 hour 13 & 14 at the Power Plant ............................................... 122
Figure 65 Day 206 hour 15 & 16 at the Power Plant ............................................... 123
Figure 66 Day 206 hour 17 & 18 at the Power Plant ............................................... 124
Figure 67 Day 206 hour 19 & 20 at the Power Plant ............................................... 125
Figure 68 Day 206 hour 21 & 22 at the Power Plant ............................................... 126
Figure 69 Day 206 hour 23 & 24 at the Power Plant ............................................... 127
Figure 70 Day 16 hour 1 & 2 at the Airport ............................................................ 129
Figure 71 Day 16 hour 3 & 4 at the Airport .............................................................. 130
Figure 72 Day 16 hour 5 & 6 at the Airport .............................................................. 131
Figure 73 Day 16 hour 7 & 8 at the Airport .............................................................. 132
Figure 74 Day 16 hour 9 & 10 at the Airport ............................................................ 133
Figure 75 Day 16 hour 11 & 12 at the Airport .......................................................... 134
Figure 76 Day 16 hour 13 & 14 at the Airport .......................................................... 135
Figure 77 Day 16 hour 15 & 16 at the Airport ........................................................... 136
Figure 78 Day 16 hour 17 & 18 at the Airport ........................................................... 137
Figure 79 Day 16 hour 19 & 20 at the Airport ........................................................... 138
Figure 80 Day 16 hour 21 & 22 at the Airport ........................................................... 139
Figure 81 Day 16 hour 23 & 24 at the Airport ........................................................... 140
Figure 82 Day 16 hour 1 & 2 at the Airport .............................................................. 142
Figure 83 Day 16 hour 3 & 4 at the Airport .............................................................. 143
Figure 84 Day 16 hour 5 & 6 at the Airport .............................................................. 144
Figure 85 Day 16 hour 7 & 8 at the Airport .............................................................. 145
Figure 86 Day 16 hour 9 & 10 at the Airport ............................................................ 146
Figure 87 Day 16 hour 11 & 12 at the Airport .......................................................... 147
Figure 88 Day 16 hour 13 & 14 at the Airport .......................................................... 148
Figure 89 Day 16 hour 15 & 16 at the Airport ........................................................... 149
Figure 90 Day 16 hour 17 & 18 at the Airport ........................................................... 150
Figure 91 Day 16 hour 19 & 20 at the Airport ........................................................... 151
Figure 92 Day 16 hour 21 & 22 at the Airport ........................................................... 152
Figure 93 Day 16 hour 23 & 24 at the Airport ........................................................... 153
List of Tables

Table 1 Monin-Obukhov Stability Category ................................................................. 24
Table 2 Summary of model versions used ................................................................. 30
Table 3 Meteorological data required by the four models ........................................ 30
Table 4 Locations of meteorological data for the Airport case ............................... 43
Table 5 Summary of monthly mean NO\textsubscript{x} concentration at Tung Chung ........ 53
Table 6 Summary of monthly maximum NO\textsubscript{x} concentration at Tung Chung .... 53
Table 7 Attributes of stacks of the Power Plant ....................................................... 59
Table 8 Locations of Meteorological data for the Power Plant ............................... 60
Table 9 Average maximum daily mixing height by ADMS and AERMOD .............. 85
Table 10 Average minimum daily mixing height by ADMS and AERMOD .......... 85
Table 11 Detail classification of P-G stability and Stability Parameter .................. 93
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Abstract

Gaussian air dispersion models are widely used for short-range pollutant dispersion study. In Hong Kong, ISC, an old-generation model is recommended in the environment impact study while there is advance generation of models grown in much interest in environmental field. The objective of this study is to investigate how Gaussian air dispersion models perform under Hong Kong scenario in order to find out which model would be the best candidate for replacement and at the same time provide some guidelines on applying Gaussian air dispersion models.

In this study, four Gaussian air dispersion models, namely ISC3, AUSPLUME (two old-generation models), AERMOD and ADMS (two advance models) are examined under Hong Kong meteorological conditions in two cases of study, one is the Hong Kong International Airport and the other one is the Castle Peak power plant. The results showed that these four models never agreed in the modeling results, due to various implementations of the dispersion equation and the meteorological processor. Advance models are preferred to the old ones due to better meteorological sense, discrete P-G stability class vs. continuous stability. Between the advance ones, ADMS is recommended over AERMOD due to several reasons. Firstly stability parameter estimated by ADMS’ meteorological pre-processor matched better with the observed stability than the one by AERMOD’s meteorological pre-processor, which is a crucial parameter in determining the dispersion parameters. Secondly, ADMS provides more functionality in modeling dispersion in urban region for instance setting minimum M-O length and street canyon model.
Chapter 1
Introduction

1.1 Background

Human activities are always associated with pollution. No matter it is a construction or demolition of a large facility like an airport, or day-one operation of a factory of heavy industry, travelling on the road with your automobiles, or even doing some cooking at your kitchen, waste residues by our activities are introduced to the surrounding. It is just about how much quantity those waste residues are. Of course, doing some simple cooking at home or driving your car at countryside would not cause much pollution problem. But we are talking about tons of household in a same area, thousand of automobiles on the traffic, a whole district of heavy industry operating days and nights. It could become a disastrous pollution problem if our wastes are released without any mitigation or control. To overcome this problem, it is standard in worldwide to perform an environmental impact assessment (“EIA”) in planning activities potentially arising pollution. Regarding to the air pollution, Gaussian air dispersion models are the models commonly used to estimate the potential direct impact to the surrounding air quality.

Gaussian air dispersion models are extensively used on short-range pollutant dispersion studies. They are important tools to assess environmental impacts of atmospheric releases in order to issue planning permission and site operation license. They can also be applied to help estimate immediate impact of accident discharges and support crisis management decision. Despite of its wide applicability, Gaussian models are simple in concept, ease to use but still consistency with the randomness nature of dispersion. They require relatively low computational power, i.e. stand-alone PC is more than enough and they have quick turn-around time for results comparing to other physical, numerical and mesoscale models. All of these factors make Gaussian air dispersion models popular and are widely adopted by environmental
agencies, consultancies and researchers all over the world.

Based on the same principle of Gaussian air dispersion equation, various generations, versions, or approaches of dispersion models have been released by different developers. Older version of Gaussian models, namely ISC (a US model), AUSPLUME (an extension of ISC by Australian) and CALINE4 (specially decided to handle traffic pollution), which operate on single module based on simple Gaussian air dispersion equation with discrete stability classes, have been under application for many years since they are invented. Advance generation of models, namely ADMS (a British model) and AERMOD (a new generation of ISC), which applies non-uniform Gaussian air dispersion equation with continuous stability class and requires meteorological pre-processing, have been of great interest to public for their adaptation of latest research in atmospheric physics. Despite of the new breakthrough in atmospheric physics, each of these models, both advance and old ones, is recommended by different environmental agencies in the world and is put into frequent application for local regulatory purposes.

1.2 Situation in Hong Kong

In Hong Kong, ISC is the Gaussian air dispersion model, together with Model FDM and CALINE4, officially accepted in the EIA process by Environmental Impact Assessment Ordinance. ISC has been widely used on different EIA projects since the ordinance is enforced in 2002. However, newer versions of Gaussian air dispersion models evolve and equip with better application on dispersion calculation based on recent research. With more interest to environmental protection grown by public, frequent occurrence of severe adverse visibility episodes as well as violations of air quality objectives (“AQOs”), Hong Kong Environmental Department (“HKEPD”) has the need to investigate the feasibility of either replacing the old models with the advance ones or including advance models in the official list in additional to the old ones. If the advance models are capable of doing a better job than the old ones as it claims, they should be providing us a better estimation on air quality impact.
potentially caused by target projects in order to make better use of emission quota without leading to violation of AQO or causing adverse effect on sensitive receptors.

To determine which Gaussian dispersion model is the best among all, we need past scientific proofs and verification under Hong Kong meteorological conditions. However, no past literature has proven which model outperforms other, although each model has been well studied. All these models, namely ISC, AUSPLUME, ADMS and AERMOD, performed very well with their own set of field data but showed discrepancies to each other in results, even they are all based on the same Gaussian dispersion theory. All these information in available literature are ineffectual to make decision on the newly recommended model. In regard to the need, the present comparative study is conducted.

1.3 Scope of the study

The best way of carrying this study is to put Gaussian air dispersion models in application to real case studies. The models can go through EIA process in order to reveal any difficulties may encounter in serious application. Four candidate models, namely ISC, AUSPLUME, ADMS and AERMOD, are investigated by applying to two local sources in Hong Kong, Hong Kong International Airport (“the Airport”) and Castle Peak Power Station (“the Power Plant”). These case studies not only facilitate the model comparison by comparing model performance on two different source type, area sources in the Airport while point sources in the Power Plant. But also these infrastructures carry environmental significance in Hong Kong, because pollutions from traffic and power generation are the major sources of pollutant in Hong Kong due to lack of heavy industry. Brief conclusion on air quality impact bought by two namely case studies will be presented.

The study is focused mainly on how much discrepancy in results among models and what causes such discrepancy. Through the investigation we justify which model would be more logical sound under Hong Kong meteorological conditions, and making recommendation on the replacing model based on the strength of the
Gaussian air dispersion models: handy, accuracy and efficiency. The study sticks strictly on performance speaking. No recommendations would be made on changing any intrinsic build of models to adapt meteorological condition of Hong Kong in order to enhance performance. Despite lack of detailed technical information of certain models, such recommendations involve intense collection of field data and model tuning. Technically the model being modified ultimately becomes a new model. It is not the intent of this study, not to mention requiring extra funding as well as time invested.

The brief flow of this study is as below. Chapter 2 presents more details about the four candidate models as well as the core of the model, Gaussian air dispersion models and its necessary parameters, which models the condition of the dispersion condition. Models of old generation make use of discrete stability classes while advance models use more realistic continuous stability in calculation. Literatures about the four models are presented in this chapter as well.

Detailed case studies, the Airport and the Power Plant are presented in chapter 3. Common features of candidates are shown through their modelling results. These results lead to brief conclusion to the air quality impact bought by the target sites. Regarding to the Airport, sensitive receptor at Tung Chung was not stroke hard due to the prevailing wind direction at the airport site for landing and take-off purposes. The emission of Power Plant does not strike hard to nearby surrounding due to the high chimney height. The plume hits the ground at further distance but is subject to inhomogeneous wind field condition which is not capable for Gaussian air dispersion models.

Chapter 4 focuses on the discrepancies in result revealed in the case studies. Models of old generation generally produce higher estimates than those by new generation and unreasonably high sometimes. Distinguishable plume structures are modelled by old models due to the use of discrete stability class. Spiked results by AERMOD are caused by unreasonable low mixing height, estimated by its meteorological pre-processor. ADMS so far performs the most reasonably and its
meteorological pre-process matches the better with observed stability than the one by AERMOD.

Chapter 5 concludes that ADMS is the most logical sound based on the two case studies. In general, it is difficult to verify the accuracy of the plume structure of each model by simply one or two reference reading. Analysis on modelling results has to go along with meteorological data no matter which model you are applying. In other word, modelling results meeting AQO does not necessarily mean the emission at acceptable level as meteorological data could go wrong and leads to wrong interpretation.
Chapter 2
Gaussian Air Dispersion Models

Gaussian air dispersion models are extensively used on short-range pollutant dispersion studies. They are important tools to assess environmental impacts of atmospheric releases in order to issue planning permission and site operation license. They can also be applied to help estimate immediate impact of accident discharges and support crisis management decision. Gaussian air dispersion models are popular and are widely adopted by environmental agencies, consultancies and researchers all over the world. As a routine tool for regulatory purpose, Gaussian models are preferred over other physical, numerical and mesoscale models in certain ways (Hanna, 1982):-

- Analytical and conceptually appealing;
- consistent with the randomness nature of dispersion;
- computationally cheaper to use;
- an official blessed status in regulatory guidelines (U.S. Environmental Protection Agency, 1986, 1996)

However, what is Gaussian air dispersion equation exactly? In this chapter, a brief introduction to Gaussian air dispersion equation is given, together with all necessary parameters both observable and estimated. It also shows how boundary layer condition is parameterized to describe the state of convection within the mixing layer. With different ways of handling the parameterization, different models and versions are evolved. Brief background information about each candidate models, namely ISC, AUSPLUME, ADMS and AERMOD are shown in the later chapter as well as literature review related to past work of comparison of these four candidate models’ performance.
2.1 Gaussian Plume Dispersion Equation

Plume Release
As you observe a plume released in a chimney far away, you see the plume goes along the prevailing wind direction while meandering both vertically and laterally due to local turbulence until the plume is diluted and no longer to be visible. This is how plume behaves in nature. In Gaussian air dispersion models, they assume that the average concentration distribution of the plume over time is a Gaussian distribution. This assumption can be traced back to the observation of molecular (Brownian) diffusion made by Roberts (1923). At any particular instance the actual concentration can be very different from the one by the Gaussian distribution, which is higher than the predicted over time but it follows Gaussian distribution, when the plume meandering about the centre plume line (Figure 1). As long as the dispersion and a long-time average is concerned (i.e. hourly average and annual average), Gaussian air dispersion models provide a simple but excellent way to overcome the randomness nature of meandering plume.

Figure 1 Instantaneous and corresponding ensemble averaged plume (Lakes Environmental)
General Gaussian Plume Equation

In general, Gaussian plume equation for a continuous point source in uniform wind with homogeneous turbulence as shown below is used in calculating pollutant concentration in short-range dispersion models.

\[
C = \frac{Q_s}{2\pi \sigma_z \sigma_y} e^{-\frac{y^2}{2\sigma_y^2}} \left\{ e^{-\frac{(z-z_p)^2}{2\sigma_z^2}} + e^{-\frac{(z-z_p+h)^2}{2\sigma_z^2}} + e^{-\frac{(z-z_p-h)^2}{2\sigma_z^2}} \right\}
\]

The concentration \(C\) is clearly in a form of Gaussian distribution function. This can be derived simply from the assumption of Gaussian concentration distribution in \(y\) and \(z\) direction at any cross section in the plume downwind of the source and integral mass conservation condition.

The plume equation can be divided into four parts, each of which carries its own physical meaning in dispersion:

1. **Emission \(Q\):** It stands for the emission strength or emission rate total emission of a specific pollutant over a period of time. If Gaussian air dispersion equation is integrated over the whole space, the total concentration equals to the total emission. In other words, the mass is conserved in it;

2. **Reciprocal of mean wind speed \(U\):** The concentration of pollutant is inversely proportional to mean wind speed. The stronger the wind, the lower the concentration is. The plume goes downwind of the mean wind;

3. **Lateral dispersion function \(F_y\):** It describes the degree of spread perpendicular to wind direction. The concentration is normally distributed laterally with the highest value at the centreline. Besides, it is inversely proportional to lateral dispersion factor \(\sigma_y\);

4. **Vertical dispersion function \(F_z\):** It describes the degree of spread in vertical direction, starting at an elevated height above the ground. The concentration distribution is the sum of Gaussian distribution from a real and three imaginary sources. The latter simulate pollutants reflected from the ground and the top of the mixing layer \(h\) after releasing at chimney height \(z_p\). The term is inversely proportional to vertical dispersion factor \(\sigma_z\).
Most of the parameters stated in the equation can be measured directly: the total emission amount or emission rate can be taken at an emission source of interest; the mean wind speed can be obtained at the anemometer near the source. On the contrary, lateral and vertical dispersion factors $\sigma_y$ and $\sigma_z$ can hardly be so measured. One way of estimation of lateral and vertical dispersion factors is by a set of dispersion curves obtained from field data. Each dispersion curve describes the factors as a function of distance from the source under one of stability classes. These curves are obtained from experimental data. Other methods such as derivations from the statistical theory relation may also be adopted. Based on this fundamental equation for point source, other equations for non-point source emission can be derived. Sources like line sources, area sources and volume sources, together with point sources, are common source types supported by Gaussian air dispersion models.

**Restriction of Gaussian Plume Equation**

Theoretical basis for Gaussian models is limited to idealized uniform wind field, same wind speed and direction with homogeneous turbulence over the whole modelling domain. It is also restricted to application to short-range impact assessment as long as Coriolis effect is neglected and the homogeneous wind field is maintained. For continuous point and line sources, mean wind speed is also required to be larger than the standard deviation of turbulence velocity fluctuations, so that upstream or longitudinal diffusion can be neglected. However, mean wind and turbulence in the planetary boundary layer rarely satisfies the above simplified assumptions of the theory. Ones encounter significant wind shears, inhomogeneities of turbulence and weak winds to make the theoretical basis of Gaussian modelling somewhat tenuous, if not totally invalid.

**2.2 Boundary Layer Parameters**

Despite the Gaussian air dispersion equation itself, some models require sufficient information about the stratification condition within the planetary boundary layer to determine the degree of mixing resulting in dispersion calculation.
Some key meteorological data parameterized include mixing height $h$, stability class, and Monin-Obukhov length. Besides their vital information each parameters carry, most arguments of this study are associated with these parameters.

2.2.1 Mixing Height

The mixing depth $h$ is the most important parameter in the dispersion calculation. It not only specifies the height at which the reflection of concentration occurs in the boundary layer but also other parameters like stability parameter $h/L$ and scales related to turbulence and diffusion. Mixing height can be actually measured onsite by sounding units like Lidar. Direct measurement is most desirable for dispersion modelling. In the absence of direct measurement, one has to estimate $h$ using some diagnostic or prognostic relations. The general formula of mixing height is as below

$$ h \propto (u_*, L) $$

2.2.2 Pasquill-Gifford Stability

In dispersion calculation, stability is the key factor that determines the dispersion pattern occurring under given meteorological condition. It usually involves in determination of dispersion parameters in respect to downwind distance. Dispersion parameters are the parameters actually appear in the Gaussian air dispersion equation, in another word, describing the dispersion pattern to the equation. If a model fails to estimate accurate stability of a specific hour, it fails the first step of dispersion calculation too.

Pasquill-Gifford stability scheme consists of seven stability classes (A-G) which ranges from stable, neutral and unstable conditions. Each class describes the same stability throughout the whole boundary layer. It implies that the stability is the uniform throughout the whole boundary layer. There is still doubt on the uniformity of stability throughout the whole atmospheric boundary layer. The scheme determines current stability by current wind strength, cloud cover, and solar radiation or solar
angle. In another word, it is a summary of all necessary meteorological condition at a specific moment. Below Figure 2 shows the detailed classification scheme of P-G classes.

<table>
<thead>
<tr>
<th>Class</th>
<th>Definition</th>
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<tbody>
<tr>
<td>A</td>
<td>Extremely unstable</td>
</tr>
<tr>
<td>B</td>
<td>Moderately unstable</td>
</tr>
<tr>
<td>C</td>
<td>Slightly unstable</td>
</tr>
<tr>
<td>D</td>
<td>Neutral</td>
</tr>
<tr>
<td>E</td>
<td>Slightly stable</td>
</tr>
<tr>
<td>F</td>
<td>Moderately stable</td>
</tr>
</tbody>
</table>

Table 1. Pasquill-Gifford stability classes

<table>
<thead>
<tr>
<th>Surface wind speed (m/s)</th>
<th>Day with insolation</th>
<th>Night</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strong</td>
<td>Moderate</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>A-B</td>
</tr>
<tr>
<td>2.3</td>
<td>A-B</td>
<td>B</td>
</tr>
<tr>
<td>3-5</td>
<td>B</td>
<td>B-C</td>
</tr>
<tr>
<td>5-6</td>
<td>C</td>
<td>C-D</td>
</tr>
<tr>
<td>6</td>
<td>C</td>
<td>D</td>
</tr>
</tbody>
</table>

Table 2. Guidelines for determining Pasquill-Gifford stability classes

Figure 2 Pasquill-Gifford stability classes and classification scheme

Each stability class has its own respective Pasquill-Gifford curves for lateral and vertical dispersion parameters ($\sigma_x$ and $\sigma_z$) separately (Figure 3). Practically, equations that approximately fit the P-G curves are used for calculation of dispersion parameters. However, the predicted concentrations by two models could still be in great difference, even though both models are applying P-G stability theory. These P-G curves are model dependent, which are derived from field experimental data for model finetuning. This is also the key element that differentiates one model to another.
Figure 3 Variation of $\sigma_x$ and $\sigma_z$ with downwind distance for the six Pasquill-Gifford stability classes

2.2.3 Monin-Obukhov Similarity Theory

The Monin-Obukhov similarity theory has been found to be more appropriate and widely accepted for stratified surface layer of the atmosphere. It is based on the similarity hypothesis proposed by Monin and Obukhov (1954), which stipulates that mean gradients and turbulence characteristics of a stratified surface layer depend only on the height $z$, the kinematic surface stress $\tau_0/\rho$, the kinematic heat flux $H_0/\rho c_p$, and the buoyancy variable $g/T_0$. The buoyancy length scale, also known as the Monin-Obukhov length $L_{MO}$ (“M-O length”) is a measure of the depth of the near-surface layer in which shear effects are likely to be significant under any stability condition and is in below form

$$L_{MO} = \frac{-u_*^3}{\kappa g F_{\theta_0} / \left( \rho c_p T_0 \right)}$$

where $u_*$ is frictional velocity at the earth’s surface, $\kappa (=0.4)$ is the von Kármán constant, $g$ is the acceleration due to gravity, $F_{\theta_0}$ is the surface heat flux, $\rho$ and $c_p$ are the density and specific heat capacity of air respectively and $T_0$ is the surface temperature. The physical meaning of M-O length represents the depth of layer above ground under which mechanical mixing is the dominant form of turbulence.

Figure 4 shows the different regions of the boundary layer in terms of the stability parameter $h/L_{MO}$ and $z/h$ where $z$ is the vertical height. The boundary layer structure is defined in terms of two variables, $h/L_{MO}$ and $z/h$, replacing the uniform stability by P-G stability formulation, varies crucially since the variation of boundary layer properties with height can be included. However, there is no exact correspondence between two schemes, as many difference combination values of $h$ and $L_{MO}$ may associate to the same P-G stability classes. The figure also shows the corresponding range of $h/L_{MO}$ approximately to the P-G stability classes. Below Table 1 summarizes the M-O stability category in short.
Figure 4 Dimensional Representation of variation of Monin-Obukhov length with atmospheric stability (manual of ADMS-Urban version 1.6, CERC, 2001)

<table>
<thead>
<tr>
<th>Stability</th>
<th>Monin-Obukhov Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stable</td>
<td>$h/L_{MO} \geq 1$</td>
</tr>
<tr>
<td>Neutral</td>
<td>$-0.3 \leq h/L_{MO} \leq 1$</td>
</tr>
<tr>
<td>Convective (Unstable)</td>
<td>$h/L_{MO} \leq -0.3$</td>
</tr>
</tbody>
</table>

Table 1 Monin-Obukhov Stability Category

Under unstable situation, the magnitude of the M-O length is a measure of the height above the ground which convective turbulence, turbulence motions caused by convective motions due to surface heating is dominant over the mechanical turbulence generated by shears. In general, convective turbulence dominates most portion of the boundary layer while the importance of mechanical turbulence is restricted within a shallow layer above ground only. Typical example moment is a sunny day with intense surface heating from sun.

In neutral condition, mechanical turbulence dominates the whole portion of boundary layer. It usually occurs when wind speed is high and it is under cloud condition. The mixing within the layer is solely the action of turbulence due to
friction of earth surface.

In stable situation, the boundary layer consists of a few dense layers above the ground. These layers suppress the vertical mixing by both convective and mechanical turbulence. The M-O length becomes a measure of the height above the ground which vertical turbulent motion is greatly inhibited by the stable stratification.

2.3 The Four Models

The Gaussian air dispersion equation or dispersion module alone cannot capture all possible features of a plume. The equation requires other modules to finish the task. For instance, a plume rise module handles how far in vertical direction the plume goes before dispersion begins. Dry and wet deposition modules handle the pollutant loss by deposition and precipitation wash-out. Meteorological pre-processor is responsible for parameterization of the boundary layer conditions. A chemical module simulates the possible chemical reactions taking place. All of these components integrate together and become a stand-alone Gaussian dispersion model.

2.3.1 Conventional Models

Older version of Gaussian models, namely ISC (a US model) and AUSPLUME (an extension of ISC by Australian), which operate on single module based on simple Gaussian air dispersion equation with discrete P-G stability classes, have been under application for many years since they are invented. Figure 5 shows the typical flow of old generation models. Dispersion module requires input of emission rate, details of sources, meteorological data, other onsite parameters like surface roughness and optional terrain information. Modelling results are output in text format for further presentation of results i.e. contour plotting or time series of concentration. Although both ISC and AUSPLUME use the same P-G stability input for dispersion calculation, they in fact apply different dispersion curve equation, which leads to different dispersion parameters $\sigma_y$ and $\sigma_z$ used in the similar dispersion equation. It is the underlying reason why modelling results of ISC and AUSPLUME are different though
these two models have the same input and setup.

**ISC**

The Industrial Source Complex (ISC) is a model developed by US Environmental Protection Agency. ISC uses equation for rural by Turner, 1970 and urban one by Briggs, 1976. It has been one of their standard regulatory models since its release in 1980s. It has only been slightly modified since the release. ISC by now is the most well-known and popular dispersion model in the world. ISC does not have a meteorological pre-processor and it applies the meteorological input directly in the calculation. The required meteorological input includes wind speed, direction and atmospheric stability and mixing height. Atmospheric stability refers to discrete Pasquill-Gifford stability class (P-G stability class). Hourly mixing heights can be obtained by sounding unit like it can also be estimated by an external module RAMMET if it is not available. Mixing heights of every twelve hours are estimated first based on the mentioned primary meteorological input by a mixing height estimator. The mixing height estimator follows similar but not exact operation of AERMOD meteorological pre-processor. Then RAMMET interpolates among estimated hours and yields mixing heights of each hour. Hourly mixing heights from any other available sources such as observation or other estimators can also be used.

ISC considers modelling site either rural or urban, each of which corresponds to
different default surface roughness length.

**AUSPLUME**

*AUSPLUME* is a model whose mathematics derived by Victorian Environmental Protection Authority’s “Plume Calculation Procedure”, which is an adaptation of ISC model. It is an Australian regulatory model approved by EPA Victoria. It is designed to predict ground-level concentration or dry deposition of pollutants emitted from one or more sources which may be stacks, area sources, volume sources or any combination of these. As an adaptation of ISC, AUSPLUME does not have a meteorological pre-processor too and the preparation of meteorological input is practically the same. It also applies discrete P-G stability class. However, AUSPLUME provides additional options in dispersion settings rather than simply by default. For instance, it allows specifying dispersion curves for difference distances among choices of Pasquill-Gifford, Briggs rural and Sigma theta. AUSPLUME allows specifying surface roughness length by users in respect to the land use of modelling site instead of only two values for rural and urban area.

### 2.3.2 Advance Models

Next generation of models, namely ADMS (a British model) and AERMOD (a new generation of ISC), which apply non-uniform Gaussian air dispersion equation with continuous stability class varied with height, by Monin-Obukhov similarity theory, and requiring meteorological pre-processing, have been of great interest to public for their adaptation of latest research in atmospheric physics. Figure 6 is a typical flow of advance Gaussian air dispersion models. Meteorological data and other onsite parameters are pre-processed through which boundary layer is characterized by boundary layer parameter before entry to dispersion module. Terrain is also pre-processed prior to dispersion calculation. These two pre-processed information, together with emission data and details of sources, are passed to dispersion module to finish the calculation of concentration distribution.
Atmospheric Dispersion Modelling System (ADMS) is a British air dispersion model, the development of which was largely funded by UK government agencies. It is under substantial practices in UK and frequently modified for better performance. ADMS is an advance dispersion model in which boundary layer structure is characterised by height of boundary layer (mixing height), a length scale dependent on surface friction velocity, the Monin-Obukhov length, and sensible heat flux at the surface. Continuous stability is implemented by the stability parameter $h/L_{MO}$ which is the ratio of mixing height to Monin-Obukhov length. All of these boundary layer parameters are estimated by a built-in meteorological pre-processor. ADMS therefore requires different set of meteorological input for the parameterization purpose. ADMS allows specifying surface roughness length according to the land use of modelling site. It provides an option to specify minimum Monin-Obukhov length which avoids the stability from getting too stable for urban area. ADMS claims to have advance dispersion calculation and non-Gaussian vertical dispersion but there is no relevant technical details open to public. Regarding to complex terrain, ADMS passes through a terrain handler, FLOWSTAR, to process complicated wind field due to terrain.
AERMOD
AERMIC Model (AERMOD) is the next generation of air dispersion model after ISC and is intended to replace ISC as the standard regulatory model in USEPA. The model comprises of three components and AERMOD itself is just a dispersion module. AERMET is the meteorological pre-processor while AERMAP is the terrain pre-processor. All three models collaborate and are collectively named as AERMOD. AERMOD is an advance air dispersion model in which boundary layer conditions are parameterized similarly as ADMS. Continuous stability is implemented by the stability parameter $h/L_{MO}$ which is the ratio of mixing height to Monin-Obukhov length. AERMET is responsible for estimation of all boundary layer parameters. It requires two kinds of meteorological data for parameterization purpose. One kind is surface data which refers to primary meteorological data measurable at ground. Another kind is vertical sounding data which is essential in estimating stability and mixing height of the boundary layer. AERMET also requires value of surface roughness length for the parameterization.

Below Table 2 summarizes the versions of models to be examined in the present study. These four models are applied on two selected scenarios which are the Hong Kong International Airport and Castle Peak Power Plant in the next chapter. Table 3 summarizes all desirable input data for each candidate models. Their requirements to meteorological data vary great among all. But similarity in meteorological input follows the categories of models, conventional versus advance models.
### Table 2 Summary of model versions used

<table>
<thead>
<tr>
<th>Air Dispersion Models</th>
<th>Version</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISC</td>
<td>ISC-AERMOD Version 4.6.2 (Lakes Environmental)</td>
</tr>
<tr>
<td>AUSPLUME</td>
<td>AUSPLUME Version 5.4 (EPA Victoria)</td>
</tr>
<tr>
<td>ADMS</td>
<td>ADMS Urban Version 2.0 (Cambridge Environmental Research Consultants)</td>
</tr>
<tr>
<td>AERMOD</td>
<td>ISC-AERMOD Version 4.6.2 (Lakes Environmental)</td>
</tr>
</tbody>
</table>

### Table 3 Meteorological data required by the four models

<table>
<thead>
<tr>
<th></th>
<th>ISC3</th>
<th>AUSPLUME</th>
<th>ADMS</th>
<th>AERMOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speed</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Wind Direction</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Temperature</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Mixing Height</td>
<td>✓#</td>
<td>✓#</td>
<td>x##</td>
<td>x#</td>
</tr>
<tr>
<td>Stability Class</td>
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<td>✓*</td>
<td>x**</td>
<td>x**</td>
</tr>
<tr>
<td>Cloud Cover</td>
<td>x</td>
<td>x</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Pressure</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>✓</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>✓</td>
</tr>
<tr>
<td>Precipitation</td>
<td>x</td>
<td>x</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Albedo</td>
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<td>x</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Solar Radiation</td>
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<td>x</td>
<td>Optional</td>
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</tr>
<tr>
<td>Vertical Sounding</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>✓</td>
</tr>
<tr>
<td>Minimum Monin-Obukhov length</td>
<td>x</td>
<td>x</td>
<td>✓</td>
<td>x</td>
</tr>
<tr>
<td>Bowen Ratio</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>✓</td>
</tr>
</tbody>
</table>

# Hourly mixing height is estimated based on the primary meteorological input by RAMMET or from any available sources.

## Hourly mixing height is estimated internally by meteorological pre-processor of that model.

* If no hourly stability class data available, it is determined by Pasquill-Gifford classification scheme which is based on wind speed, incoming solar radiation and cloud cover.

** Hourly stability class is estimated internally by meteorological pre-processor of that model.
2.4 Literature Review

The four air dispersion models are all derived based on the same theory and are of different development background. There is no doubt that their internal designs, including requirement on data, flow of modules, boundary layer variable parameterization, are not identical and cause the discrepancies among modelling results. When agencies are choosing one model as their standard regulatory models, the model performance is of greater importance than which authorities is recommending it. Several studies have been conducted to address the different performance among air dispersion models.

Inter-comparison studies

The relevant comparative studies on air dispersion models involved only most of the candidate models, including ISC, ADMS and AERMOD, which are the three models commonly investigated at the same time. Although AUSPLUME is not involved in the following studies, it is assumed to behave similarly as ISC does as it is an extension of ISC.

The most straightforward way to compare model performance is to compare with field measurements. Numbers of such comparison studies have been conducted on the results of two or more models at different target sources. One of the studies involving most of the candidate models of present study is American Petroleum Institute study (Hanna et al (1999)). It comprises comparative studies of ISC, AERMOD and ADMS models against five field data sets. Three data sets are for the flat terrain (Duke Forest, Kincaid and Indianapolis), one involved building entrainment (Optex) and one topography (Lovett Field). Overall, no model performed the best all the time. Sometimes a model did better and sometimes another one became better. ISC had tendency to calculate higher concentration than AERMOD and ADMS do. AERMOD and ADMS behaved similarly but the agreement was not consistent in all five data sets.

Hall et al (1999a) pointed out that due to the inherently of high variability in field
measurement, the validation study could only indicate differences between models in terms of statistically how well the data fit. It showed nothing about why different calculations occurred between models.

The study following (Hall et al (1999b) mainly focused on the differences among ISC, AERMOD and ADMS models. Hours of specific boundary layer condition were selected to demonstrate model discrepancies under the same condition. Sensitivity tests on stack height, buoyant release, interaction with the top of boundary layer, building entrainment and topography had been conducted. Three models produced significantly different results in every case. The results of each case were highly variable against one another. There was no consistent relationship among models. The calculation of ISC and AERMOD exceeded a factor of two in 40% of the time while ADMS and AERMOD exceeded the same ratio in 30% of the time. But the high variability of differences between models makes the statistic less worth trusted. The agreement between models probably occurred in neutral stability condition near the ground. The divergence increased with increasing source height and non-neutral conditions. This relation was not consistent all the time. The study still left the cause of discrepancies not discussed.

The review of past inter-comparison (Hall et al (2000a,b) realized that a critical feature of inter-comparison appeared to be the handling of meteorological data inputs to the models, especially in the relationship between M-O length scale based input and Pasquill-Gifford stability categories. The difference of model performance appeared to originate in their meteorological pre-processors. These produced markedly different estimates of boundary layer depth for all three models, ISC, ADMS and AERMOD and of the M-O length scale for ADMS and AERMOD from the same raw data input. AERMOD persistently calculated deeper boundary layer depth than ADMS. In a brief test in which the two pre-processor outputs were input to one of the models for an annual calculation, which significantly changed the resulting concentration and overall difference reduced. AERMOD and ADMS generally showed a greater sensitivity to changes in atmospheric condition than the ISC model. Such great sensitivity produced significant differences between
predictions.

**Uncertainty study**

Same conclusion was also drawn from an uncertainty study on deriving dispersion parameters from meteorological data (Auld, et al (2002)). Boundary layer parameters estimated by meteorological pre-processor are the drives of the air dispersion models. In another word, significant sources uncertainties are due to model formulation and model physics. The study illustrated that roughness length at the meteorological site, as a parameter to pre-processor, contributes significant overall model uncertainty, while the pre-processor is insensitive to parameterisation of the surface energy budget, wind speed, direction and temperature. The choice of meteorological data for input can be of significance. A further consideration on choosing meteorological site is to ensure that the met pre-processor is supplied with accurate data specific to the site. Besides, poor agreement between models is observed under low wind speed conditions, during which peak concentrations often occur.

Based on the latest literature, instead of judging model performance by comparing predicted concentration with observation, we should pay more attention to the accuracy of parameterization of boundary layer variables. The advance models are found to be more sensitive to changes in atmospheric condition than the conventional ones. The discrepancy in modelling results thus can be traced back to the disagreement in meteorological pre-processing. Should any outstanding predictions occur among models, they should be associated with the incorrect handling of boundary layer variables in use. Furthermore, if one model can handle the characterisation of boundary layer parameters well enough, its predicted concentration becomes the most reliable and self-explainable prediction. This logic should be followed in present study.
Chapter 3
Case Studies

In order to make the model comparison more complete, different kinds of sources are needed to provide broader view on model performances for analysis. Dispersion models can handle various types of sources, commonly classified as point, line, area and volume sources. The performance on handling each type of source is of concern. Practically non-point sources (line, area and volume) share the same equation for calculation. Two types, point and non-point sources, are enough to cover the general performance of models.

On the other hand, near-ground and elevated releases require distinct considerations in calculation. Pollutants from near-ground release usually reside within the mixing height with no escape. In contrast, pollutants from elevated sources possibly interact with the top of mixing layer and escape from the mixing layer. Two cases of ground and elevated release are necessary to demonstrate the handling algorithms of models. Therefore two sources possessing distinct features are chosen.

The Airport represents an area source of ground release of NO\textsubscript{x} while the Power Plant is an elevated point release of SO\textsubscript{2}. Each one of them meets the criteria of the test cases mentioned above.

Although different target pollutants are investigated in two cases, they are the same kind of particles to dispersion models. They have no effect on the model performance unless chemical reactions are important. Furthermore, only one of the candidate models, ADMS includes an optional chemical module. Therefore the performance of the chemical module is neglected in present study.
3.1 Hong Kong International Airport

3.1.1 Background

Hong Kong International Airport (“the Airport”) is known as one of the busiest airports in the world. It situates at Chak Lap Kok, north of Lantau Island. It is 34km west of Hong Kong Island. It serves the city and functions as a hub for Mainland China and South East Asia. Hundreds of aircrafts as well as supporting vehicles and machineries operate within the airport region every day. It goes without saying that all the combustion engines emit nitrogen oxides (“NO\textsubscript{x}”). In effect the airport region is a huge NO\textsubscript{x} emitting source and indeed one of the major sources of pollutants in Hong Kong.

Unlike the old Kai Tak International Airport, the Airport is further away from the community. Yet, it is only about three kilometres away from Tung Chung District and the Country Park in Lantau Island. The HKSAR Government and the society as a whole pay close attention to the environmental condition of the airport region. If the airport was found to cause too much harm to the surrounding, further development of the region might probably be called to a halt. It is, therefore, a good exercise to investigate how the Airport has been doing to the environment so far.

Besides carrying environmental importance, the Airport consists of a typical ground-emitting source which serves model comparison purpose. Emissions are due to two kinds of activities of aircrafts, flight and maintenance. Although flight paths are climbing up in height, major emitting area is found at hanger area where maintenance of aircrafts usually takes place. With its large area in size and significant emission, the hanger area acts as a major ground-emitting source. Modelling on the Airport scenario is therefore able to show performance of each model on ground-emitting sources.
3.1.2 Case Setup

The four models may require different sets of information or format of input. For instance, AERMOD and ADMS require more meteorological data than ISC and AUSPLUME does in general. Also each model has its own setup files of unique format. Nevertheless all input data follows strictly what it is going to be presented in this section. Every model of interest is configured identically for the Airport case study.

3.1.2.1 Spatial Setup

As mentioned in the Background section, there are two different kinds of emission sources of NO\textsubscript{x} in the Airport by and large. They are flight path sources and the hanger sources. There are four official flight paths in the Airport. Each of the flight paths is identified with a code name comprising of its relative pointing direction and left or right to the pilot of incoming flights. Two flight paths (07L & 07R) run northeast towards the airport while the other two (25L & 25R) run southwest. They lay either on northern or southern edge of the Airport. Hangers are found at the centre of the airport and cover most of the facilities.

Exact locations of sources and the surrounding of the Airport are shown in below GIS map (Figure 7). Green areas are the NO\textsubscript{x} emitting sources in the Airport. Line in grey shows roads while brown area shows buildings within the region. Size, location and height of runways and hangers are provided by Hong Kong Airport Authority.
Both flight path sources and hanger sources are considered as area sources. Hanger sources are considered as area sources without doubt because of their shapes. However, flight path sources can be considered to be either line or area sources. For the purpose of model comparison in current study, the site is preferred comprising of only one type of sources. Although flight path sources are cast as area sources, the overall result does not differ much. Area sources are handled practically the same way as line sources by the four models.

Some more modifications on the sources are made due to models’ incapability. The four models support only sources at constant height. In another word, no curve and rolling surface can be modelled by models. Since flight paths are climbing continuously from the ground, they have to be broken down into several discrete horizontal elevated segments in order to input into models properly. Besides discontinuous sources, three of the models, ISC, AUSPLUME and AERMOD have height restriction on sources up to 100m only. Segments higher than 100 meters have to be restricted to 100 meters in every model.

Figure 8 shows detailed spatial setup of sources. Two large rectangular area
sources at the middle of the airport stand for the hanger sources. Black one is the emission from the ground supporting unit while red one is from the idle plane. Rest of the areas running through the airport are the flight path sources. Blue, green and yellow areas stand for paths of approaching, take-off and the climbing-up flight respectively. All declarations of sources are identical in all four models.

Figure 8 Three-dimensional view of emission sources in the Airport

3.1.2.2 Emission

Previous spatial setup section has already revealed that NO\textsubscript{x} emission in the Airport is due to several various operations. For the flight path sources, NO\textsubscript{x} is generated as a result of three aircraft operations: approaching, taking-off and climbing-up. Each operation contributes different proportion of NO\textsubscript{x} to total emission of each flight path. The emission of each flight path is directly proportional to the frequency of use. The choice of flight path is mainly determined by the current meteorological condition, such as wind direction, when an aircraft is preparing to land or depart. One flight path may be used more frequently while another one has only a few aircraft passing by. Therefore the emission rate of each flight path is highly
variable during 24 hours. For the hanger sources, NO\textsubscript{x} emission accounts for idle aircrafts and ground supporting units. Every aircrafts spend most of their time in hangers after landing and before departure. Aircrafts may have their loading or unloading, refuelling, repairing and maintenance in the hanger. Various kinds of ground supporting vehicles, such as oil tankers, transportation for ground supporting crew and cargo trucks carry out all mentioned operations. In addition, aircraft pulling units are intensively used for towing aircrafts to either the hanger for maintenance or the flight path for departure. All these ground supporting vehicles carry combustion engines and produce NO\textsubscript{x} during operation. Hanger area therefore turns into a large NO\textsubscript{x} emitting source.

Total annual emission of NO\textsubscript{x} and hourly flight count of each flight path and hanger in 2003 are provided by Hong Kong Airport Authority. Average daily emission rate of each month are obtained based on the monthly flight counts. Hourly flight count generates the hourly emission factor which describes the hourly variation on the use of the Airport. The actual emission of an hour is obtained by multiplying emission rate and the hourly factor.

Figure 9 - Figure 17 show the emission factor profile of each source in January, April, July and October 2003 respectively. There is no uniform emission profile for all flight paths in twelve months. The choice of flight path is dependent on the current wind direction when an aircraft is preparing to land or depart. The emissions of hangers usually rise starting at 9 a.m. and drop at 11 p.m. It is the busy hour that aircrafts spend their time for loading, unloading and maintenance after landing. The actual emission of flight paths is usually higher than the one of hangers.
Figure 9 Emission profile of Idle planes and APU in 2003

Figure 10 Emission profile of takeoff and climbout in the direction of 25L in 2003

Figure 11 Emission profile of takeoff and climbout in the direction of 07R in 2003
Figure 12 Emission profile of takeoff and climbout in the direction of 25R in 2003

Figure 13 Emission profile of takeoff and climbout in the direction of 07L in 2003

Figure 14 Emission profile of approach along 07L
Figure 15 Emission profile of approach along 07R

Figure 16 Emission profile of approach along 25L

Figure 17 Emission profile of approach along 25R
3.1.2.3 Meteorological data

Meteorological data is the most important information that the dispersion calculation relies on. Meteorological data by the closest available stations are used as the rule of thumb. Since the Airport requires meteorological information for aviation, most of data is recorded on site and made available to pilots and control panel. Therefore wind speed and direction, temperature, pressure and relative humidity are obtained from the AWS at Chak Lap Kok. Cloud cover is recorded at the Airport. Vertical sounding comes from observation station at King’s Park. Hourly stability at the Airport is provided by Hong Kong Observatory (“HKO”). Table 4 summarizes the location of each meteorological measurement applied in the Airport study. Missing data is generally handled by interpolation between previous and next available data. Missing wind direction is replaced by the previous available data. Figure 18 shows the distributions of wind speed and direction in January and July 2003.

<table>
<thead>
<tr>
<th>Meteorological Data</th>
<th>Location of Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Speed and Direction</td>
<td>Chak Lap Kok</td>
</tr>
<tr>
<td>Temperature, Pressure, Relative</td>
<td>Chak Lap Kok</td>
</tr>
<tr>
<td>Humidity</td>
<td></td>
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<td>Cloud Cover</td>
<td>Chak Lap Kok</td>
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<td>Stability</td>
<td>Chak Lap Kok</td>
</tr>
<tr>
<td>Vertical Sounding</td>
<td>King’s Park</td>
</tr>
</tbody>
</table>

Table 4 Locations of meteorological data for the Airport case
Figure 18 Wind Roses at the Airport in January and July 2003
3.1.2.4 Topography, Receptors and Duration

The terrain of the computational domain is flat and assumed as flat for simplicity. Major buildings within the Airport region are relatively lower in height and are considered to be similar to those commonly seen in western countries. The surface roughness thus assumes to be 0.8m, which corresponds to commercial or industrial region in western countries suggested by AUSPLUME. The region is considered as urban area for its construction and busy port. Similarly, the minimum Monin-Obukhov length in ADMS is taken as 80m to represent a less urbanized area than a large city which corresponds to 100m suggested by ADMS.

The dispersion modelling results are collected in two ways. First one is a grid of receptors with resolution 145m × 105m at ground level covers the whole airport and all sources. Figure 7 shows the computational domain which is 11.5km × 8.2km large. It is capable of showing the whole picture of air quality impact around the Airport. Second one is a point receptor placed exactly at Tung Chung air monitoring station. It tells how the Airport is affecting the nearby sensitive community, Tung Chung.

In order to demonstrate model performances under various meteorological conditions, the modelling is originally planned to cover all four seasons of year 2003 in Hong Kong. However, spring and autumn are excluded for different reasons. The air traffic in spring 2003 was greatly reduced by the out break of SARS (Severe Acute Respiratory Syndrome). It probably results in a confused picture that the dispersion would be better and the air quality impact would be low during spring time. For the autumn, wind data is missing due to monitoring hardware failure. It leads to modelling on autumn impossible. Therefore only studies on winter and summer are conducted. For each modelling season, one month of time is selected to be modelled. January and July in 2003 are the modelling durations representing winter and summer times respectively.
3.1.3 Results

Three kinds of organized modelling results are going to be presented in this section. They are compact and commonly referred to tell air quality impact by one source. They include:-

i) Monthly mean contours of NO\textsubscript{x} concentration;

ii) Percentile contours of NO\textsubscript{x} concentration; and

iii) Time series on NO\textsubscript{x} concentration at Tung Chung air quality monitoring station.

3.1.3.1 Comparison of Monthly Average Model Predictions

Figure 19 shows the contours of mean NO\textsubscript{x} concentration in January and July 2003 calculated by each model. All modelling results show the similar air quality impact by the Airport. Higher NO\textsubscript{x} concentrations over the hangers are commonly noticed in all modelling results. The concentration over hangers ranged from 30 to 90\(\mu\text{g/m}^3\) in January and from 30 to 80\(\mu\text{g/m}^3\) in July. NO\textsubscript{x} concentration dropped significantly once it was outside the hanger areas. The concentration was 20\(\mu\text{g/m}^3\) or below in both months. The air quality impact caused by the Airport is acceptable in a monthly sense and it is less in summer time than the one in winter time.

Nevertheless modelling results neither agree exactly with any others despite of the modelling durations. They are different in both magnitude and distribution of concentration. Overall in two modelling months, January and July of 2003, AUSPLUME predicted the highest mean concentration in general followed by AERMOD, ADMS and ISC. AUSPLUME also predicted the widest spread and the rest follows the same previous order in magnitude, but ISC appeared to be wider than ADMS did.
Figure 19 Mean Contour in January and July 2003 at Airport
Figure 20 100th percentile contours in January and July 2003 at Airport
Figure 21 99th percentile contour in January and July 2003 at Airport
Figure 22 98th percentile contour in January and July 2003 at Airport
3.1.3.2 Comparison of Percentiles of Model Predictions

Figure 20 shows the contours of 100\textsuperscript{th} percentile of hourly NO\textsubscript{x} concentration in January and July 2003 calculated by each model. 100\textsuperscript{th} percentile prediction is also known as the worst case prediction. A large amount of NO\textsubscript{x} concentration over hanger areas has been recorded by all models in the worst case. The NO\textsubscript{x} concentration over hangers ranged from 400 to 1400\textmu g/m\textsuperscript{3} in January and from 150 to 1000 \textmu g/m\textsuperscript{3} in July. The one outside the Airport ranged from 20 to 400\textmu g/m\textsuperscript{3} in both months. It was again lower than the hanger areas. However, the modelling results violated the hourly objective of 300\textmu g/m\textsuperscript{3} given by the Environmental Protection Department (“EPD”) in Hong Kong.

Similarly to monthly mean results, no models produced same results with one another. The difference among models in the worst case is even larger than the one in monthly mean. It usually exceeds a factor of three between any models. The ranking of models in the order of descending concentration changes as well. AERMOD became the model predicting the highest concentration in the worst case among the four models. AUSPLUME predicted the second highest in the worst case, which was originally the top one in monthly mean. ISC predicted higher worst case concentration but lower monthly mean than ADMS did. ADMS predicted the least concentration among the four. The change in ranking implied that some models behaved differently under certain circumstances.

Figure 21 and Figure 22 show the contours of 99\textsuperscript{th} and 98\textsuperscript{th} percentiles respectively. The NO\textsubscript{x} concentrations of smaller percentile become lower as expected. It retreats and maintains high concentration around the hangers and downwind of ambient wind. At the same time, Tung Chung region is suffered from slight NO\textsubscript{x} concentration. Summarizing all percentile results shown before, the Airport brings severe air quality impact to hanger areas and ambient downwind region occasionally.

For the difference between modelling results in 99\textsuperscript{th} and 98\textsuperscript{th} percentiles, the ranking of models in descending order follows the same as the one of 100\textsuperscript{th} percentile
concentration. However, the difference becomes less when smaller $n^{th}$ percentile was considered. It implies that the performance of the four models approached each other in more general case.

### 3.1.3.3 Comparison of Times Series of Model Predictions

Figure 23 are the time series of NO$_x$ concentration at Tung Chung in January and July 2003 respectively. The plots of all four months did not show continuous reading of NO$_x$ concentration as wind direction was ever-changing during the modelling period. When wind is blowing from the northwest of the Airport, the plume probably hits Tung Chung and produces a reading. There is no reading for the rest of wind directions. Furthermore, the dominant wind usually comes from the north in winter time while it comes from the south in summer time. This is the reason why the point receptor recorded more frequent and higher reading during winter time than summer time.

For the model performance, no models produce the same results with any other models. AUSPLUME generated the highest result throughout most of the modelling duration. ISC followed the next. ADMS’s prediction was slightly higher than that of AERMOD during most of the modelling time. In particular sudden increases of NO$_x$ concentration appeared in AERMOD from time to time. AERMOD usually became the highest predicting model when the sudden increase happened. Its concentration was so high that they should be responsible for part of the readings captured in 100$^{th}$ percentile contours in AERMOD. The sudden increase indicates that AERMOD would behave extremely high in concentration prediction under certain conditions.

Figure 24 shows all modelling results comparing with the official observation of NO$_x$ concentration released by EPD. The modelling results were incomparable with the observation. Table 5 and Table 6 show the summaries of monthly mean and maximum NO$_x$ concentration by all models and the observation respectively. The mean modelling results constituted only around 2% of the observation. The maximum
modelling results are at least 50% less than the one of observation. The Airport brings only slight air quality impact to the nearby Tung Chung community. NO\textsubscript{x} from sources other than the Airport play more significant role in affecting Tung Chung. These background sources are strong and should come from far away since no major emitting sources are found nearby.

<table>
<thead>
<tr>
<th>Mean NO\textsubscript{x} ((\mu g/m^3))</th>
<th>Observation</th>
<th>ADMS</th>
<th>AERMOD</th>
<th>ISC</th>
<th>AUSPLME</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>100.60</td>
<td>1.44</td>
<td>1.73</td>
<td>1.41</td>
<td>3.14</td>
</tr>
<tr>
<td>July</td>
<td>25.70</td>
<td>0.21</td>
<td>0.20</td>
<td>0.18</td>
<td>0.46</td>
</tr>
</tbody>
</table>

Table 5 Summary of monthly mean NO\textsubscript{x} concentration at Tung Chung

<table>
<thead>
<tr>
<th>Max. NO\textsubscript{x} ((\mu g/m^3))</th>
<th>Observation</th>
<th>ADMS</th>
<th>AERMOD</th>
<th>ISC</th>
<th>AUSPLME</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>464.22</td>
<td>30.31</td>
<td>228.29</td>
<td>64.43</td>
<td>106.00</td>
</tr>
<tr>
<td>July</td>
<td>154.98</td>
<td>12.64</td>
<td>46.80</td>
<td>20.99</td>
<td>45.70</td>
</tr>
</tbody>
</table>

Table 6 Summary of monthly maximum NO\textsubscript{x} concentration at Tung Chung
Figure 23 Time series of NOx concentration in January and July 2003 at Tung Chung by models
Figure 24 Time series of NOx concentration at Tung Chung in January and July 2003 with the observation
3.1.3.4 Air Quality Impact

In this chapter, the dispersion problem of the Airport is studied. The four models are applied to calculate the NO\textsubscript{x} dispersion from the Airport. All models are setup identically to best describe the scenario. However, no exactly the same modelling results are produced. And their rankings differ for every type of modelling results. AUSPLUME is the model predicted the highest monthly mean contour but the second highest in percentile contour following AERMOD. ISC and ADMS also have their rankings in monthly mean and percentiles interchanged.

The story about the ranking in point receptor at Tung Chung is more complicated. AUSPLUME predicted the highest concentration during most of the time, followed by ISC. Different from all mentioned long-term averaged results, ADMS predicted higher concentration than AERMOD during most of the time in time series. But AERMOD produced sudden increase of NO\textsubscript{x} concentration which is so high and make AERMOD become the highest predicting model in certain hours. Certain conditions in AERMOD must be accounted for the sudden increase. This is going to be discussed further in Chapter 4.

Despite of the different model performances, current study is still capable of showing the air quality impact caused by the Airport. The air quality impact is acceptable over the region in a monthly mean sense. Models successfully point out that the air quality possibly violates the NO\textsubscript{x} objective given by EPD. For Tung Chung community, the Airport brings only a few percent of the observed NO\textsubscript{x} concentration. Modelling results has no way to be comparable to the observation. It implies that stronger background sources are acting on the Tung Chung for the major NO\textsubscript{x}. These sources should be far from Tung Chung since there are no other significant sources nearby.
3.2 Castle Peak Power Station

3.2.1 Background

Castle Peak Power Plant (“the Power Plant”) is one of the major plants in Hong Kong, owed by Castle Peak Power Company Limited. It locates at Tap Shek Kok in Tuen Mun, north-western part of Hong Kong. It is a coal-burning power plant, no doubt a source of sulphur dioxide (“SO₂”). Two stations, namely station ‘A’ and station ‘B’ are found there and have separate exhaust chimneys. Each chimney connects with four power generating units, 350MW each at station A and 677.5MW each at station B. Total electricity capacity of the Power Plant is 4110MW. The Power Plant is a typical coal-fire power plant as well as a SO₂ emitting source. Hong Kong is lack of heavy industrial which emits large amount of SO₂. In effect the Power Plant is a major source of SO₂ in Hong Kong.

People argue that the increasing emission of power plants is responsible for recent poor visibility problem in Hong Kong. However, Hong Kong is undergoing further development which will require more power in the future. More power generation results in more emission of pollutants. If the power plant is found to be the cause of poor visibility, the power companies may consider either using less sulphur content coal, installing sulphur removing equipment or investing clean energy such as wind energy to satisfy the increasing demand of power without bring addition burden to Hong Kong air. The decisions of the power companies affect the sustainable development of Hong Kong on the other end. A dispersion study on the Power Plant should provide more or less useful information for the decision maker.

Similar to ground releasing area sources in the Airport, the Power Plant is another good case study for model comparison purpose. It has two stacks above 200m which are perfect candidate to show model performances on elevated point sources. The setup is relatively simpler than the Airport and is capable of revealing more features of the four models.
3.2.2 Case Setup

Similar to the Airport case study, the four models may require different sets of information or format of input. Also each model has its own setup files of unique format. Nevertheless all input data follows strictly what it is going to be presented in this section. Every model of interest is configured identically for the Power Plant case study.

3.2.2.1 Spatial setup

Since there are only two sources in the Power Plant case, the setup is relatively simpler. Two elevated point sources is setup to represent the two chimneys of separate stations. Both are similar in structural sense. Attributes of the two point sources are summarized in below Table 7. Exact locations of the two sources and the surroundings are shown in Figure 25.

![Figure 25 GIS map showing the Power Plant setup](image)
3.2.2.2 Emission

Total annual emission amount of SO$_2$ and hourly emission profile of every month in 2004 are obtained from Emission Inventory. Monthly emission can be deducted based on the 12-months hourly emission profile. Station B has a high emission rate than Station A. Summer days consumes more power than winter time for air conditioning such that the emission is higher in summer. Figure 26 shows the hourly emission profile of January, April, July and October in 2004. The hourly emission profile correlates with typical hourly power loading profile. The emission is lower at midnight since the city sleeping and the power consumption is low. It goes higher during working hour as offices and industries demand higher power. It then drops a little bit when working hour ends. It gradually decreases afterward till midnight.

![Emission profile of Castle Peak Power Station](image-url)

Figure 26 Hourly emission factor profile of the Power Plant
3.2.2.3 Meteorological data

As a rule of thumb, data from the closest available stations are collected for input. Hourly wind speed and direction and stability at Black Point, which is 4 km away from the Power Plant, are provided by HKO. Temperature, pressure, and relative humidity are obtained from the AWS located at the Power Plant. Cloud cover data is recorded at Hong Kong International Airport. Vertical sounding comes from observation station at King’s Park. Below Table 8 summarizes the location of meteorological measurement used in the Power Plant case. Missing data is generally handled by interpolation between previous and next available data. Missing wind direction is replaced by the previous available data. The distribution of wind speed and direction in different months are also shown in Figure 27 for reference.

Instead of mixing height estimated by RAMMET, the hourly mixing height estimated by ADMS is used for the input to ISC and AUSPLUME. RAMMET estimated consistently high mixing heights in the previous case study (Detail can be referred to 4.1.4). But ADMS was capable of estimating more reasonable mixing height. The performance is improved if more appropriate mixing height is used.

<table>
<thead>
<tr>
<th>Meteorological Data</th>
<th>Location of Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Speed and Direction</td>
<td>Black Point</td>
</tr>
<tr>
<td>Temperature, Pressure, Relative</td>
<td>Castle Peak</td>
</tr>
<tr>
<td>Humidity</td>
<td></td>
</tr>
<tr>
<td>Cloud Cover</td>
<td>Chak Lap Kok</td>
</tr>
<tr>
<td>Stability</td>
<td>Black Point</td>
</tr>
<tr>
<td>Vertical Sounding</td>
<td>King’s Park</td>
</tr>
</tbody>
</table>

Table 8 Locations of Meteorological data for the Power Plant
Figure 27 Wind Roses at the Power Plant in January, April, July and October 2004

### 3.2.2.4 Topography, Receptors and Duration

For simplicity, the computation domain is considered as flat terrain again, despite of a low hill north of the Power Plant. The surface roughness is assumed to be 1.0m in order to account for the height of the stacks. The minimum Monin-Obukhov length in ADMS is taken as 30m to represent an industrial region suggested by ADMS.

The computational domain is 12km × 12km large with the sources at the centre. A grid of receptors with resolution 150m × 150m at ground level is used over the domain.

In order to demonstrate model performances under various meteorological
conditions, the dispersion calculation is performed in all four seasons of year 2004 in Hong Kong. One month of every season is selected to be the modelling duration. They are January, April, July and October, representing winter, spring, summer and autumn respectively. Four months in total should be able to provide sufficient data for the analysis on the air quality impact of the power plant and model performance.

3.2.3 Modelling Results

Two kinds of organized modelling results are going to be presented in this section. They are compact and commonly referred to tell air quality impact by one source. They include:-

i) Monthly mean contours of SO$_2$ concentration;

ii) Percentile contours of SO$_2$ concentration.

3.2.3.1 Comparison of Monthly Average Model Predictions

Figure 28 and Figure 29 show the monthly mean SO$_2$ concentration contour of each modelling month. All models show low monthly mean SO$_2$ concentration of 10 – 20µg/m$^3$. The air quality impact in SO$_2$ is acceptable since it is far below the annual SO$_2$ objective of 80µg/m$^3$ given by EPD.

Once again, no modelling results agree with any of other models. AERMOD and ADMS produced similar contours while ISC and AUSPLUME produced their similar one. Each pair also calculated similar order of concentration. AERMOD and ADMS gave concentration around 20µg/m$^3$ which is a double of ISC and AUSPLUME, around 10µg/m$^3$. The difference noticed here is too huge for models of the same kinds. Underlying factors should have played the role.

In particular, AERMOD was the model predicting the highest SO$_2$ concentration in every modelling month, followed by ADMS. Concentration in AERMOD appeared closer to the sources than the one in ADMS. ADMS extended concentration further away from the sources. ISC predicted slightly higher concentration than AUSPLUME did. ISC produced plumes with longer tails while AUSPLUME produced rounder
shape of plumes. The ranking of models is completely different from the one of monthly mean in the Airport case.

3.2.3.2 Comparison of Percentiles of Model Predictions

Figure 30 and Figure 31 show the contours of 100\textsuperscript{th} percentile of every modelling month. The air quality impact in the worst case is acceptable in every modelling result. No models produced more than the hourly SO\textsubscript{2} objective of 800μg/m\textsuperscript{3} given by EPD in all modelling months. ISC predicted maximum concentration of 500μg/m\textsuperscript{3}, 450μg/m\textsuperscript{3} for AERMOD, 250μg/m\textsuperscript{3} for ADMS and 150μg/m\textsuperscript{3} for AUSPLUME in the worst case.

All contours show typical multiple-lobed pattern radiating from the sources but there are significant difference in maximum concentration and contour distribution. ISC predicted the highest worst case, followed by AERMOD, ADMS and AUSPLUME. Maximum concentration of ISC and AERMOD occurred close to the sources while the one of ADMS and AUSPLUME were further away. ISC had the least lateral spread of such that fringes of low concentration were obvious. AUSPLUME had the widest spread and was followed by AERMOD.

Figure 32 – Figure 35 show the contours of 99\textsuperscript{th} and 98\textsuperscript{th} percentile of each modelling month. The ranking in concentration followed the same as 100\textsuperscript{th} percentile. In general, more concentration loses in small n\textsuperscript{th} percentile. ISC and AUSPLUME are found to lose too much if they are comparing with the other two models. Their percentile contours showed nothing in the area where obvious plumes did exist in the other contours. Such loss of concentration is commonly found in both 99\textsuperscript{th} and 98\textsuperscript{th} percentile results. It possibly leads to the low monthly mean concentration in ISC and AUSPLUME shown in the previous section.
Figure 28 Monthly mean contours in January and April 2004 at Castle Peak
Figure 29 Monthly mean hourly contours in July and October 2004 at Castle Peak
Figure 30 100th percentile contours in January and April 2004 at Castle Peak
Figure 31 100th percentile contours in July and October 2004 at Castle Peak.
Figure 32 99th percentile contours in January and April 2004 at Castle Peak by ISC
Figure 33 99th percentile contours in July and October 2003 at Castle Peak by ISC
Figure 34 98th percentile contours in January and April 2004 at Castle Peak
Figure 35 98\textsuperscript{th} percentile contours in July and October 2004 at Castle Peak
3.2.3.3 Air Quality Impact

In this chapter, the dispersion problem of the Airport is studied. The four models are applied to calculate the SO$_2$ dispersion from the Airport. All models are setup identically to best describe the scenario. Once and again, none of the four models agree with each another. Each ranking of specific type of modelling results is never the same. For monthly mean concentration, AERMOD is the model predicting the highest concentration, followed by ADMS. ISC and AUSPLUME predicted only half concentration AERMOD and ADMS did. However, for the worst case, ISC predicted the highest one among the four models. Some factors should be responsible for the sudden change in performance. Furthermore, ISC and AUSPLUME are found to have lost concentration when considering 99$^{th}$ and 98$^{th}$ percentile results. The loss of concentration leads to the low monthly mean concentration. They are both caused by the same reason which is going to be discussed in later section.

Although the four models consider the impacts differently, they still provide necessary information to estimate the air quality impact by the Power Plant. All models showed low monthly mean SO$_2$ concentration of 10 – 20$\mu$g/m$^3$. The worst hourly SO$_2$ concentration ranges from 150 to 500$\mu$g/m$^3$ and it is under the hourly objective. The Power Plant brings only slight air quality impact.
Chapter 4
Discussion

Besides air quality impact, two case studies in the last chapter have demonstrated discrepancies in model performances among the four models. Four different Gaussian air dispersion models are applied in each case study. All models are setup identically for each case study, however, no same modelling results are generated.

The most important goal of this study is to show which model is the most appropriate to be applied in Hong Kong. The analysis could be very straight forward by matching the modelling results with the observations. However, the previous two case studies agree that both studied regions are under influence by stronger background sources than the target sources. Pollutant concentrations emitted by the target sources are incomparable with the observation. It is impossible to tell which model is better than another without a proper reference. A few more reference concentrations at different locations are actually required to completely verify the accuracy of the dispersion spread predicted by models. Furthermore, model performances are subject to different scenarios. A model predicts the highest concentration among the four in one case but it may predict the least in another case. The performances are highly variable that no general relation among models is available. Therefore the best model cannot be obtained by straight-forward concentration comparison due to mentioned problems.

Recalling from the literature review, instead of judging model performance by comparing predicted concentration with observation, we should pay more attention to the accuracy of parameterization of boundary layer variables. The advance models are found to be more sensitive to changes in atmospheric condition than the conventional ones. The discrepancy in modelling results thus can be traced back to the disagreement in meteorological pre-processing. If one model can handle the characterisation of boundary layer parameters well enough, its predicted
concentration becomes the most reliable and self-explainable prediction. Furthermore, how the discrepancies among models resulting in difference in regulatory decision should be considered as well.

As regulatory purposes are concerned, the applicability of models on Hong Kong, carries a significant importance. Hong Kong is a rocky, highly urbanized island region where complex terrain and heat island effect play important roles in air dispersion. Models which are capable of handling these characteristics of Hong Kong should be credited.

Other characteristics of models are of interest too during selecting the official regulatory air dispersion model. The technical requirement of each model is concerned as it leads to the starting and running cost of the model. Productivity of each model is subject to their time take for a run, as regulatory processes are carried out very frequently. No doubt the model with the shorter runtime but better performance is usually preferred.

4.1 Performance discrepancies and their causes

The modelling results in the two scenarios have showed the possible impacts brought by the infrastructures in Hong Kong. More importantly they have demonstrated how differently the four models performed. No models agree with each another. The performances of the four models are inconsistent in the two scenarios and are dependent on the setups. They are highly variable that no general relation among models is available. All of these agree with the findings in the previous studies.

In the result sections, all modelling results are organized and presented in contours of mean concentration and percentiles. Although differences among models can be identified easily from these plots, these plots do not reveal any detail information on the causes of the discrepancy. They carry only summarized information over a long period but show no information of a shorter time frame. Moreover, mean concentrations possibly either amplify or conceal the difference in single hourly average due to averaging effect. Percentile results are sorted concentrations in the
order of magnitude, comparisons in which usually involve concentrations of different hours. Based on these two kinds of plots, the identification of hours having great discrepancy has already become a problem.

In order to avoid drawbacks of mean concentration and percentiles, the analysis on the causes of discrepancy should focus on the short-term average such as hourly average. Hourly average is the elemental time average unit in the calculation. The discrepancies in hourly averages probably result in the discrepancies in long-term averages and percentiles. Without any processing, the difference in hourly average purely reflects the difference in work done by the four models. Analysis on these different hourly averages is the key to produce an explanation for the different model performance. Information on this hourly basis becomes the major focus in the following analysis.

4.1.1 Disappearing Plumes in ISC and AUSPLUME

In order to have a better understanding of dispersion behaviour of each model, more attention should be paid to hourly results. After considering all hours in July, the day on 24\textsuperscript{th} July 2004 is selected to illustrate detail evolution of hourly plumes. All 24-hours results are shown in Appendix A. Two colour codes are used to indicate two different ranges of concentration. The magenta colour represents concentration in a range of 0 to 10μg/m\textsuperscript{3} while the red colour represents higher range of concentration up too 500μg/m\textsuperscript{3}. The four models commonly predicted very little or close to null concentration from the hour 23 to hour 6 of the next day. Thus all the plots within this period were in magenta colour. ADMS was the only model showing a slight plume at hour 1, 2 and 3.

AERMOD was the first model showing red colour contour in the morning. The red plume first appeared at hour 7 while others had no plumes at all. ADMS started to show a purple plume at hour 8 and a red one later at hour 9. However there was none for ISC and AUSPLUME until hour 10. For most of the daytime during hour 10 to 17, all four models show an obvious red plume radiating from the point sources. When the
time came past hour 17, the concentrations dropped significantly in ISC and AUSPLUME. Only magenta plume left in these two models but ADMS and AERMOD still predicted a red plume. The situation persisted until hour 23 at which plumes of all models disappeared.

Take modelling results at hour 15 (Figure 65) illustration for different dispersion patterns offered by the four models. The stability at that time was unstable condition. ADMS showed a triangular shape of plume. The ones of AERMOD and AUSPLUME both were in a round shape but the contour in AERMOD concentrated more on the side near the sources. The contour of AUSPLUME spread further and extended out of the modelling domain. ISC showed the narrowest plume which was round at the tip close to the sources. Even in the same stability, the dispersion pattern of each model is entirely different from another.

The most astonishing modelling results of ISC and AUSPLUME occurred at the hours 13 and 14 (Figure 64). While every model still showed red plumes at the hour 12, the plumes in these two models had completely gone for the coming two hours. The plumes resumed at the hour 15. The emission never stopped during all these hours. ISC and AUSPLUME should be responsible for the disappearance of the plumes. Such disappearance of plumes at daytime together with low concentration at the early morning and the later afternoon caused the two models omitting too much pollutant in the mean concentration calculation. The mean concentration was of course 60% lower than those of ADMS and AERMOD. The cause for the disappearance of plumes should be investigated.

In the Power Plant case, ISC and AUSPLUME predicted no obvious plume in the early morning, later afternoon or even at noontime. It is distinct from other model predictions. There are two reasons for the disappearance of plumes. The first reason is due to the height of the mixing layer and the assumption of no particle exchange between the two layers. If the plume is released above the mixing layer, no pollutant can hit the ground. The ground concentration is zero when the mixing height falls below the stack. On the other hand, the ground concentration is also zero when the mixing height is low and the plume rise is strong enough. When the exhaust leaves the
exit of the stack, it rises for some distance before dispersion starts, due to either momentum or buoyancy. If the plume rise is high enough, the plume reaches the top of the mixing layer and interacts with the layer. In ISC and AUSPLUME, the penetration is considered as complete penetration if the plume rise is strong enough. Due to no particle exchange between layers, the plume would never re-enter the mixing layer again thus the ground concentration is recorded as zero.

Figure 36 shows the time series of mixing height on the day 24 in July 2004. ISC and AUSPLUME used the mixing height estimated by ADMS in their calculation. According to Figure 64, the mixing height below the stack height (215m) occurred at the hours from hour 1 to 5 and hour 24. Therefore no concentration was recorded in ISC and AUSPLUME at these hours. Although the mixing height was about 1000m at hour 13 and 14, the plume rise under low wind unstable condition was still strong enough for penetration. According to the plume rise formula for unstable case (Briggs 1975), the plume rise at 500m away the sources at hour 13 is obtained as follow:

\[ F_m = \left(\frac{\rho_s}{\rho}\right) r_s^2 \bar{w}_s^2 = 756.65 \text{m}^4 \text{s}^{-3} \]

\[ F_b = (1-\frac{\rho_s}{\rho}) gr_s^2 \bar{w}_s = 1084.91 \text{m}^4 \text{s}^{-3} > F_m \]

.: The plume rise is buoyancy driven.

The plume rise due to buoyancy is \( z_c' = 1.6 F_b^{\frac{1}{3}} (\bar{u})^{-1} x^{\frac{2}{3}} = 1242 \text{m} \)

The plume rise was higher than the mixing height. Thus the plume penetrated and did not hit the ground at hour 13. The plume rise at hour 14 was even higher as the wind speed was 0.6m/s only. The plume disappeared in the same way in both hours 13 and 14.

Another reason for the disappearance is that the plume travels out of the domain without contacting with the ground. The plume actually lies outside the modelling domain. It is purely due to the built-in dispersion curves. ISC and AUSPLUME consider less dispersion occurred in neutral and stable conditions. A narrow plume with a long tail is usually found in neutral condition. The plume is even narrower and with longer tail in stable condition. When the source is elevated, the plume in neutral
or stable case requires longer distance to hit the ground. If the domain is close to the source, no ground concentration can be recorded.

If the modelling domain is extended from 12km × 12 km to 40km × 40km, the plume will be noticed again. Figure 38 demonstrate the contour of extended domain at hour 7. The plume first hit the ground at around 5km in ASUPLUME and 6.6km in ISC. The contour shown in the original grid in AUSPLUME was in fact the tip of the plume (Figure 61\(^1\)). The plume lay beyond the first hitting point with the ground. The emission from the point sources could even reach the Airport of the opposite shore. The situation also happened on the other hours given that it was under neutral or stable case and no interaction with the top of a mixing layer. These hours included from hour 6 to 9 and from hour 18 to 22.

![Mixing Height at Castle Peak on 24th July 2004](image)

Figure 36 Time series of mixing height at the Power Plant on 24\(^\text{th}\) July 2004

\(^1\) The purpose of the figure is solely showing that the plume exists and lies outside the original domain. The concentration, shape and location of the plume are invalid because the wind field over such a large domain is not uniform.
Stability at the Power Plant on day 24th July 2004

![Stability Parameter h/LMO](Image)

Figure 37 Time series of stability parameter at the Power Plant on 24th July 2004

**ISC AUSPLUME**

![Contour plots](Image)

Figure 38 Contour plots of 40km × 40km over the Power Plant at hour 7 on day 24 in July 2004

### 4.1.2 Nighttime Concentration Peaks in AERMOD

In the Airport case study, AERMOD exhibit similar monthly mean concentration of NO\textsubscript{x} with other models. But it generates the highest worst case concentration among the four models. With only 2% less percentile, the concentration is 3 times less than the worst case. The concentration during most of the modelling hours should be much lower in order to maintain fairly similar monthly mean concentration with others.

\[2\text{ It shows only the schematic stability of ISC and AUSPLUME. These two models use P-G stability class which does not linearly related to the stability parameter } h/L_{stg}. \text{ Detail can be referred to Figure 4.}\]
AERMOD should have generated sudden peaks at certain hours and relatively low concentration in most of the time. These features of modelling results have been further confirmed by time series of concentration at a point receptor. Time series has already demonstrated its strength in revealing the discrepancies among the four models. Hourly concentration contours should be paid more attention in the later text.

With the guidance by the time series results, the day 16\textsuperscript{th} January 2003 is selected to illustrate detail evolution of plumes over 24 hours. Hourly NO\textsubscript{x} concentration contours are shown in Appendix B.

At most of the hours, Tung Chung was away or just touches the boundary of the plume. Only an hour at hour 18 (Figure 78) the plume directly hit Tung Chung district. It is the reason why the observation did not pick up reading continuously throughout the time. The occurrence of reading is purely wind driven.

Although AERMOD produces the highest reading at Tung Chung at hour 18, it is not the model predicting the highest at most of the time. According the general structure of plume at earlier hours, AUSPLUME usually calculates the highest concentration and the widest spread of the plume. AERMOD was the model predicting the least during the time.

However the performance of AERMOD had suddenly changed since hour 18. AERMOD predicted high concentration while the emission went down after sunset. Plumes of darker colour were commonly noticed in the later hourly contour plot. In particular at hour 20, 22 and 24, AERMOD produced the darkest red plume, the highest concentration in another word. The concentration in AERMOD was constantly 200 above the others inside and 100\text{µg/m}^3 above outside the Airport.

The times that AERMOD predicted the highest are more frequent than the expected. AERMOD has predicted the highest concentration for 4 times during 24 hours of day 16. But only one occurrence is indicated by the times series plot (Figure 23). There should be parameters account for these high predictions.

Highly concentrated plumes usually appear after sunset. If the mixing height is considered together with the concentration, the highly concentrated plume is correlated with the low mixing height estimated in AERMOD. Figure 39 show the
time series of mixing height during the day 16. The least mixing height on day 16 was 75m above ground in AERMOD. The mixing height could reach 51m the least in January. The mixing height is not necessarily 51m for the occurrence of the severe plume. The lower the mixing height, the severer the plume is. And the effect is more obvious for a near-ground release of pollutants. When this shallow mixing layer occurs, the ground released pollutant is compressed within such thin mixing layer, well mixed and travel along the wind direction. The concentration predicted by AERMOD becomes the highest among the four. The concentration at Tung Chung indicates the happening of this only when the wind direction favours. In another word, the occurrence of the highly concentrated plume is more frequent than it is shown from the concentration time series at Tung Chung. However the shallow mixing layer does not necessarily lead to the highest concentration among the four models. The actual amount of concentration is also subject to the dispersion pattern at that hour.

Figure 39 Time series of mixing height on 16th January 2003 at the Airport
Figure 40 Time series of reciprocal Monin-Obukhov length on 16th January 2003 at the Airport

Figure 41 Time series of stability parameter at the Airport on 16th January 2003

The occurrence of such shallow mixing layer can be found at nighttime of both winter and summer. It is usually in stable condition. If the benchmark of 100m is considered, there are 34 hours in January and 32 hours in July that the mixing height is less than or equal to the benchmark. It constitutes less than 5% of the modelling time.

3 P-G stability classes used in ISC and AUSPLUME do not linearly related to the stability parameter $h/L_{MO}$. More detail can be referred to 2.2.3.
such that the mean concentration is not affect greatly.

ISC and AUSPLUME predicted the second highest plumes. They are nothing about the mixing height as the mixing height is relatively high and fluctuates around 2km. The concentrated plume at ground level is purely the product of the built-in dispersion curves and a ground release source. In stable condition, dispersion curves of ISC and AUSPLUME describe relatively narrower plume which remains about the same height after release. Pollutants are also more concentrated along the plume centre line. For such a ground release in the Airport, the plume resides close to the ground when stable condition occurs. Ground receptors probably experience highly concentrated pollutants together by the plume and the ground reflection. Therefore ISC and AUSPLUME show severe air pollution problem whenever stable conditions occur.

4.1.3 Low wind condition in ADMS

Sometimes the resulting plume in ADMS pointed away from plumes of other models. ADMS result in Figure 64 in Appendix A is an example. The direction of the plumes of ADMS and AERMOD agreed with each other at hour 13. When the time came to hour 14, the plume of AERMOD rotated a little bit in anti-clockwise. But the plume of ADMS remained the same. Some features of ADMS should be responsible for the inconsistent plume direction.

The plume direction in ADMS is sometimes inconsistent with the ones of other models. It points away from the input wind direction. The cause for the inconsistency is due to the correction on wind component by ADMS. In ADMS, the minimum allowable wind speed is 0.75m/s. If input wind speed is lower than the minimum allowable value, the meteorological processor replaces the wind speed with that value. And the wind direction is taken as the previous valid one. The plume then travels in a different direction from the input one. However, the solution is simple and straight-forward. Instead of correction by ADMS, the correction is done manually in data preparation stage by replacing the low wind speed as the minimum allowed value.
and leaving the direction untouched. The resulting plume then follows the same as the input wind direction.

No matter what, ADMS still has the highest minimum allowable wind speed 0.75 m/s while AERMOD uses a threshold $\sqrt{2} \sigma_{v, \text{min}}$, equivalent to 0.28 m/s. Peak concentrations are usually predicted to occur under low wind speed conditions. Handlings of low wind conditions by models therefore have to be as realistic as possible. ADMS is unable predict the peak concentration well if wind cases are dominant during the duration of interest. It certainly underestimates the concentration of pollutant in low wind conditions as higher wind speed is replaced.

4.1.4 Difference in Mixing Height Predictions

Mixing height $h$ not only specifies the thickness of boundary layer within which mixing occurs but also essential parameters like stability parameter and scales related to turbulence. More definition on mixing height can be referred to 2.2.1.

Figure 42 – Figure 44 show the time series of mixing height in all case studies. Mixing height estimated by RAMMET was applied in both ISC and AUSPLUME in the Airport case and it was at unreasonable trend and value for Hong Kong. In Hong Kong the only available data on mixing height are recorded at dawn and dust of each day. To fill up the gaps between data, RAMMET performs interpolation based on input like albedo and solar radiation. However, the resulting mixing height profile showed no diurnal variation and was only able to capture the trend of low frequency. It was 2.5km high above ground on average which was unreasonably high for Hong Kong. It is the reason why the mixing height by ADMS has been replaced in dispersion calculation of later Power Plant case.

Mixing heights of ADMS and AERMET share similar trend but have different magnitudes. Both mixing heights show diurnal variation in which they increase during the daytime and decrease during nighttime. AERMOD usually estimates higher mixing height than ADMS does during daytime. The difference becomes greater in summer time than in winter time. The mixing height by ADMS was below 2km on
average while the one by AERMOD reached above 3.5km and 4.0km at most. At nighttime, both mixing heights come close together but AERMOD still predicts slightly higher.

<table>
<thead>
<tr>
<th>Average Maximum daily mixing height (m)</th>
<th>Jan 03</th>
<th>Jul 03</th>
<th>Jan 04</th>
<th>Apr 04</th>
<th>Jul 04</th>
<th>Oct 04</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADMS</td>
<td>1834</td>
<td>1833</td>
<td>1760</td>
<td>2219</td>
<td>2171</td>
<td>1750</td>
</tr>
<tr>
<td>AERMOD</td>
<td>2795</td>
<td>2734</td>
<td>2956</td>
<td>3130</td>
<td>3467</td>
<td>2955</td>
</tr>
<tr>
<td>ISC &amp; AUS</td>
<td>2739</td>
<td>3026</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Table 9 Average maximum daily mixing height by ADMS and AERMOD

<table>
<thead>
<tr>
<th>Average Minimum daily mixing height (m)</th>
<th>Jan 03</th>
<th>Jul 03</th>
<th>Jan 04</th>
<th>Apr 04</th>
<th>Jul 04</th>
<th>Oct 04</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADMS</td>
<td>322</td>
<td>260</td>
<td>179</td>
<td>114</td>
<td>408</td>
<td>187</td>
</tr>
<tr>
<td>AERMOD</td>
<td>441</td>
<td>314</td>
<td>266</td>
<td>226</td>
<td>668</td>
<td>334</td>
</tr>
<tr>
<td>ISC &amp; AUS</td>
<td>1695</td>
<td>2427</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Table 10 Average minimum daily mixing height by ADMS and AERMOD

Table 9 shows the average maximum daily mixing heights by ADMS, AERMOD and ISC & AUS. Maximum mixing height usually occurs at daytime. ISC & AUS has the highest mean maximum mixing height and AERMOD estimated higher than ADMS did. AERMOD and ISC & AUS estimated mixing height at around 3.0km which is too high for Hong Kong region.

Table 10 shows the average minimum daily mixing heights by ADMS, AERMOD and ISC & AUS. Minimum mixing height usually occurs at nighttime. Mixing heights by all models lowered and came closer together at nighttime. AERMOD still predicted higher mixing height than ADMS did. ISC & AUS still maintained the mixing height at 2.0km which is definitely too high at nighttime.

Furthermore, mixing height estimated by AERMOD is too low for an urban region at some particular hours. It could reach the lowest value of 50m in the Airport scenario (Figure 42) and 20m in the Power Plant scenario (Figure 43 and Figure 44) while the corresponding ones by ADMS reached only 150m and 73m the lowest respectively. Such a low mixing height probably results in either too high concentration of pollutants for dispersion within boundary layer or too low
concentration for dispersion outside the layer.

a)

Figure 42 Time series of mixing height at Airport

b)
Figure 43 Time series of mixing height in a) January and b) April at the Power Plant
Figure 44 Time series of mixing height in a) July and b) October at the Power Plant.
4.1.5 Conventional vs. Advance models

The biggest of the conventional models concern is the dispersion physics applied. Unlike advance models they are applying dispersion theory from recent research of atmospheric physics, similarity theory, in which variable condition with height can be implemented by the ratio of mixing height $h$ to M-O length $L_{MO}$. Conventional models follow simple Gaussian dispersion theory with discrete uniform P-G stability classes throughout the whole mixing layer. Discrete uniform stability class then provokes distinct curve of dispersion factors, resulting in distinct form of plume spread, which is not realistic that plume spread is restricted to be one of the several forms, subject to the stability scheme applied.

Conventional models are also lack of meteorological processor which is handy in handling missing met input data. According to the study so far, meteorological data are the essential driving input for the air dispersion model.

4.1.6 ADMS vs. AERMOD

Advance models are known to be sensitive to the changes in atmospheric condition by the literature review. It has also been confirmed by the previous analysis and case studies. Based on this sensitivity, three statements are derived about the advance dispersion models and would become crucial features in determining the best suitable Gaussian air dispersion models for Hong Kong. They are:-

- Distinct result is accountable by boundary layer parameters;
- Difference between predicted results by models is accountable by boundary layer parameters;
- Better estimation of boundary parameters results in more reliable, more self-explainable prediction of concentration.

The first rule has been shown in the previous section, example like prediction spike by AERMOD is due to very low mixing height at the particular hour, and inconsistent plume direction by ADMS due to handling of low wind conditions by met
Regarding the second rule, it can be verified by replacing meteorological parameters of AERMOD into ADMS. It can be understood as the difference in modelling results is minimum, and pure work by dispersion modules, if same set of boundary layer parameters are used to drive the dispersion calculation. Boundary layer parameters are said to be dominant factors in discrepancy of modelling results if ADMS behaves similarly to AERMOD with replaced parameters. At the same time it implies that better estimate of boundary layer parameters describing the mixing layer should result in better predictions of concentration.

With the third rule, estimated stability by ADMS and AERMOD are matched with the observed P-G stability obtained from the Hong Kong Observatory. The model with better matching stability estimates the boundary layer parameters better under Hong Kong meteorological condition and thus it is capable of generating the more reasonable results among the candidate models. That model should earn more creditability towards official model in EIA ordinance in Hong Kong.

### 4.1.6.1 Test One: Replaced Meteorological Input to ADMS

The simple test is to rerun the Day 16 at the Airport again by ADMS, keeping all existing setup and parameters except replacing boundary layer parameters by the one of AERMOD into ADMS for the same setup of scenario. The detail resulting plots can be found in Appendix C together with their own original met parameter for ADMS and AERMOD. The result is obvious that all 24 hours of contours by ADMS with replaced met parameters, particularly night hours (Figure 45 and Figure 46), came closer to the prediction by AERMOD while differentiating from the original ADMS results. Dispersion modules of ADMS and AERMOD are found to be not much in difference. It proves the evidence that the boundary layer parameters are the crucial drive to the dispersion calculation. Different boundary layer parameters results in different predictions by models. It also implies that better prediction on concentration can be obtained with better estimated boundary layer parameters.
Hour 21

ADMS

ADMS with AERMOD met pre-processor

AERMOD

Hour 22

Figure 45 Hourly contour of NOx concentration at hour 21 & 22 on Day 16 at the Airport
Figure 46 Hourly contour of NOx concentration at hour 23 & 24 on Day 16 at the Airport
4.1.6.2 Test Two: Predicted Stability vs. Observed

In test two, estimated stability by ADMS and AERMOD are matched with the observed P-G stability obtain from the Hong Kong Observatory (“HKO”). More definition of stability can be referred to 2.2.2 and 2.2.3. In order to collaborating two different definitions, stabilities are classified simply into stable, neutral and unstable conditions. Detail classification is presented in below Table 11 (Lyneham, 1995).

<table>
<thead>
<tr>
<th>Atmospheric Stability</th>
<th>P-G stability class</th>
<th>Stability Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stable</td>
<td>E, F</td>
<td>$h/L_{MO} \geq 2$</td>
</tr>
<tr>
<td>Neutral</td>
<td>D</td>
<td>$-0.6 &lt; h/L_{MO} &lt; 2$</td>
</tr>
<tr>
<td>Unstable</td>
<td>A, B, C</td>
<td>$h/L_{MO} \leq -0.6$</td>
</tr>
</tbody>
</table>

Table 11 Detail classification of P-G stability and Stability Parameter

According to the classification scheme, stabilities in the two case studies are worked out. All stabilities used by the four models in calculations are presented together to see how well they match with each another. Figure 47 and Figure 48 show the percentage number of three stability classes over the modelling durations in the two case studies. P-G stability classes used by ISC and AUSPLUME are officially released by the HKO and corrected in respect to the sounding information at King’s Park. It has more credit in accuracy and reliability. Therefore stabilities by HKO is taken as reference to justify the performance of ADMS and AERMOD in terms of stability estimation.

The stability classes estimated by AERMOD mainly falls into stable and unstable cases. AERMOD consistently estimates low percentage of neutral case in respect to HKO. Neutral case occurred less than 20% of the time generally in all case studies and is only one-third of the HKO.

On the other hand, stabilities of ADMS and HKO are similar in proportion and the difference of each class is commonly within 10% in all cases. Obviously ADMS is more capable of capturing observational stability than AERMOD. Anyway, the
proportion of each stability class never agrees among the three kinds.

Besides percentage of stability by each model, it is also interesting to see how well they match with each another hour-by-hour. Figure 49 – Figure 54 show the hour-by-hour matching of stability among ADMS, AERMOD and HKO in all two case studies. Each plot compares a pair of models at one time. It shows the percentage hour of stability combinations. There are nine possible stability combinations in total (stable & stable, stable & neutral, stable & unstable, neutral & stable, and so forth). The three bars diagonally from left to right represent the percentage hour of matched stability, which are stable & stable, neutral & neutral and unstable & unstable respectively. Two models are said to have similar stability conditions applied in calculation if these three diagonal columns are significant.
Figure 47 Percentage of stability in different models at the Airport

Figure 48 Percentage of stability in different models at the Power Plant
a) AERMOD vs. HKO

![Graph showing percentage of matching and disagreement between AERMOD and HKO]

- Percentage of Matching: 65.5%
- Percentage of Disagreement: 34.5%

b) ADMS vs. HKO

![Graph showing percentage of matching and disagreement between ADMS and HKO]

- Percentage of Matching: 72.4%
- Percentage of Disagreement: 27.6%

c) AERMOD vs. ADMS

![Graph showing percentage of matching and disagreement between AERMOD and ADMS]

- Percentage of Matching: 73.4%
- Percentage of Disagreement: 26.6%

Figure 49 Percentage of Matching Stability in January 2003 at the Airport
Figure 50 Percentage of Matching Stability in July 2003 at the Airport
a) AERMOD vs. HKO

b) ADMS vs. HKO

c) AERMOD vs. ADMS

Figure 51 Percentage of Matching Stability in January 2004 at the Power Plant
a) AERMOD vs. HKO

![Graph showing percentage of matching and disagreement between AERMOD and HKO in April 2004 at the Power Plant.](image)

**Figure 52** Percentage of Matching Stability in April 2004 at the Power Plant.

Percentage of Matching: 62.2%
Percentage of Disagreement: 37.8%

b) ADMS vs. HKO

![Graph showing percentage of matching and disagreement between ADMS and HKO in April 2004 at the Power Plant.](image)

**Figure 52** Percentage of Matching Stability in April 2004 at the Power Plant.

Percentage of Matching: 78.8%
Percentage of Disagreement: 21.3%

c) AERMOD vs. ADMS

![Graph showing percentage of matching and disagreement between AERMOD and ADMS in April 2004 at the Power Plant.](image)

**Figure 52** Percentage of Matching Stability in April 2004 at the Power Plant.

Percentage of Matching: 78.9%
Percentage of Disagreement: 21.1%
a) AERMOD vs. HKO

Figure 53 Percentage of Matching Stability in July 2004 at the Power Plant
a) AERMOD vs. HKO

Figure 54 Percentage of Matching Stability in October 2004 at the Power Plant
For the matching between AERMOD and HKO (Figure 49a – Figure 54a), there are significant number of unmatched neutral cases in general, though stable and unstable cases match well with the observation. Neutral cases of HKO match with all three stabilities of AERMOD in similar portions. It is due to less estimated neutral case in AERMOD. With less number of neutral case in AERMOD, neutral case of HKO has to match with other stabilities else. It agrees with what has been shown previously in percentage number of stabilities.

For the matching between ADMS and HKO (Figure 49b – Figure 54b), stabilities of ADMS matched well with the one of HKO above 70% of all time and there are three apparent bars of matched stability. Bars of other stability combination are much lower in height. So most of the time ADMS is capable of describing stability close to the actual situation

Nevertheless, P-G stability class and stability parameter are two different definitions. Agreement in stability class does not necessarily mean that they are having exactly the same stability condition applied in dispersion calculations.

Besides, AERMOD and ADMS matched well on the stable and unstable cases (Figure 49c – Figure 54c), although there are significant portion of 15% - 25% unmatched cases on neutral stability by ADMS. It agrees on the fact shown earlier that ADMS predicted more neutral cases than AERMOD did. Although AERMOD and ADMS use the same similarity theory for meteorological parameterization, they show disagreement in stability parameters. Stability parameter is defined as mixing height over the Monin-Obukhov length \( \frac{h}{L_{MO}} \). Investigation on this parameters should be able to reveal an explanation for the disagreement.
Comparing Monin-Obukhov length

M-O length $L_{MO}$ is the height above ground under which mechanical turbulence is important. It separates the boundary layer into two affected by different turbulence. It then determines the stability parameter $h/L_{MO}$ together with mixing height $h$ in AERMOD and ADMS. More definition of M-O length can be referred to 2.2.3. Since stability parameter depends extensively on the magnitude both directly and indirectly ($h$ depends $L_{MO}$ too), and the sign of M-O length, difference in M-O length leads to different dispersion pattern and then dispersion results.

Figure 55 and Figure 56 show the time series of M-O length by AERMOD and ADMS at the Airport and the Power Plant respectively. The first feature to be noted is that the M-O length of ADMS is capped to prevent from boundary layer condition going too stable for an urban region. The capped value is 0.0125 for the Airport case (Figure 55) and a higher value of 0.03 for the Power Plant case (Figure 56), which is equivalent to the minimum M-O length of 80m and 30m specified respectively.

In general, M-O lengths by the two models matched very well around the value zero, which is a typical value under neutral boundary condition. But they do not agree well if M-O lengths fell away from zero. Also, AERMOD estimated higher magnitude than ADMS did no matter which the sigh M-O length was. It implies that stability in AERMOD always goes more extreme than the one in ADMS. Unstable cases are more unstable in AERMOD since turbulent and convective mixing is more vigorous. Similarly, stable cases are calmer in AERMOD due to stronger stratification prohibiting turbulence. AERMOD therefore estimated less neutral cases while more stable and unstable cases occurred.

Furthermore, difference in M-O lengths also results in different structure of boundary layer. M-O length tells not only the degree of mixing but also the height above ground under which mechanical turbulence is important. Mixings above and below M-O length is due to different kinds of dominant turbulence. Different M-O lengths then result in entirely different distribution of dominant turbulence, despite of stability.

Even stability parameters of AERMOD and ADMS are classified in the same
stability class, they are in fact referring to different boundary condition. Due to difference in M-O lengths, stability in AERMOD goes more extreme ends than the one in ADMS. And the two models apply different structures of boundary layer at the same time. Therefore the disagreement of stability between AERMOD and ADMS is even worse than shown in previous section.

4.2 Model Runtime

In general, ISC and AUSPLUME take less runtime for a run than ADMS and AERMOD do. The major reason is the additional runtime for the extra modules to conventional models. The runtime difference is more significant on calculation of contours or grids of receptors than a few single point receptors.

For single receptor case, such as Tung Chung as the only receptor at the Airport, all four models took only 2-3 minutes to finish the calculation for a month of hourly meteorological data. For a grid of receptors like the contour generated in the Airport case, ISC and AUSPLUME took 5-6 hours of calculation while ADMS and AERMOD took around 10 hours for a month of hourly data. Regarding the power plant case, the runtime followed similarly but subject to the difference of receptors used. Runtime of advance Gaussian air dispersion models is around a double to the conventional one due to more sophisticated model physics and model implementation.

From previous section, we know that advance models implement recent research atmospheric physics and return with more detail parameters used on calculation, which provides essential information on verifying predicted concentrations. All these new elements and breakthrough in advance models take only a double more runtime than the conventional one, not to mention the machine nowadays are getting more powerful in a short cycle, which means advance models can return results in a shorter time but remains informative as design.
Figure 55 Time series of reciprocal Monin-Obukhov length at Airport
Figure 56 Time series of reciprocal Monin-Obukhov length in a) January and b) April at Castle Peak
Figure 57 Time series of reciprocal Monin-Obukhov length in c) July and d) October at Castle Peak
Chapter 5
Conclusion

As far as the regulatory purpose is concerned, below aspects should be considered when picking the most appropriate of Gaussian air dispersion models for Hong Kong:

- Model physics
- Applicability
- Performance
- Uncertainty
- Technical requirement and runtime

Conventional models (ISC and AUSPLUME) and advance models (ADMS and AERMOD) applied separate atmospheric physics on handling dispersion calculation. Conventional models make use of Pasquill-Gifford stability classes to describe the boundary layer condition as a whole such that uniform stability through out the whole mixing depth. But in fact boundary condition is so variable that the discrete uniform stability class is incapable of describing the exact picture. The types of dispersion on conventional models are confined to available step functions in terms of stability classes. These models are incapable of accounting all possible dispersion behaviours in the calculation.

Advance models implement recent research on atmospheric physics in which the boundary condition is parameterized by Monin-Obukhov length, mixing height and any other parameters. Continuous stability parameter is applied instead of discrete stability classes. The boundary layer condition variable to the height is made possible in the dispersion modelling. Mechanical turbulence dominates the layer near the ground while convective one dominates the upper layer under the unstable condition. Even if it is stable stability, mixing due to wind shear is still important near ground surface. Although the model physics of advance models sound more realistic than the conventional. The decision should still be subject to the performance of individual
models and verifications to the field data.

Air dispersion modelling over Hong Kong region requires some more applicability. Hong Kong is well known to be a highly urbanized harbour with rocky terrain over the region. The wind field is impossible to maintain homogeneity due to the rocky terrain. Plumes might split or spread around the hill.

The most important goal of this study is to show which model is the most applicable to Hong Kong meteorological conditions. The analysis could be very straightforward by matching the modelling results with the observations. However, the previous two case studies agree that both studied regions are under influence by stronger background sources than the target sources. Pollutant concentrations emitted by the target sources are incomparable with the observation. It is impossible to tell which model is better than another without a proper reference. A few more reference concentrations at different locations are actually required to completely verify the accuracy of the dispersion spread predicted by models. No conclusion on the best model can be straightforwardly made.

Recalling form the literature review, instead of judging model performance by comparing predicted concentration with observation, we should pay more attention to the accuracy of parameterization of boundary layer variables. The advance models are found to be more sensitive to changes in atmospheric condition than the conventional ones. The discrepancy in modelling results thus can be traced back to the disagreement in meteorological pre-processing. If one model can handle the characterisation of boundary layer parameters well enough, its predicted concentration becomes the most reliable and self-explainable prediction.

As regulatory purposes are concerned, the applicability of models on Hong Kong, carries a significant importance. Hong Kong is a rocky, highly urbanized island region where complex terrain and heat island effect play important roles in air dispersion. Models which are capable of handling these characteristics of Hong Kong should be credited.

Other characteristics of models are of interest during selecting the official regulatory air dispersion model. The technical requirement of each model is
concerned as it leads to the starting and running cost of the model. Regulatory processes are carried out very frequently that the time of each model run taken results in the productivity of the model. Of course the model with the shortest runtime considering the most aspect of air dispersion should be recommended.

Recalling the three statements about advance Gaussian air dispersion models:-

- Distinct result is accountable by boundary layer parameters;
- Difference between predicted results by models is accountable by boundary layer parameters;
- Better estimation of boundary parameters results in more reliable, more self-explainable prediction of concentration.

From the past section, both ADMS and AERMOD generated outstanding predictions and the causes are from the inappropriate estimation of meteorological parameters. The first statement provides leads to explain the causes of outstanding prediction as well as spotting the potential problem during the dispersion calculation. The overall problem in ADMS is minor that those of AERMOD and can be easily overcome without involving any complication calculation. With second statement, the performance of dispersion modules of ADMS and AERMOD is not much different from each other. The meteorological parameters thus are the dominant drive of the dispersion modules. With the third statement, stability parameters estimated by ADMS and AERMOD have matched with observed stability classes, and ADMS is found to be capable of best describing the boundary layer condition occurring in Hong Kong. ADMS should be able to generate the most reasonable predicted results among all.

Although ADMS is the most recommended model among the four, none of the four models is perfect in the performance. ADMS is the only model that performs reasonably in all modelling scenario. Every model has its own shortcomings according to its implementation.

ISC and AUSPLUME both are old generation of Gaussian air dispersion models. They make use of Pasquill-Gifford stability class to describe the whole boundary layer in a single condition. But the boundary condition is so variable that the discrete
stability class is incapable of describing the exact picture. Furthermore, the types of dispersion pattern are confined to available stability classes. These two models do not consider all possible dispersion behaviours in the calculation. In the Power Plant case, these two models demonstrate the feature of complete penetration of the plume through the top of the mixing layer. However partial penetration and particles exchange between layers are widely accepted. At the same time, the complete penetration of plumes is responsible for 60% less mean concentration than other two models predict. Almost a double of the expected threat is introduced to the environment if the regulatory decision is made based on either ISC or AUSPLUME. The practices of these two models potentially lead to wrong decision that brings adverse effect to the environment. For all these above these two models should be excluded from the candidate list.

AERMOD performs in more reasonable way than ISC and AUSPLUME does. It is an advance dispersion model in which the boundary condition is parameterized. Continuous stability parameter is used instead of discrete stability classes. However, the boundary condition mainly goes either stable or unstable. Neutral case rarely occurs. Also, the model prefers more extreme boundary layer conditions. The unstable condition is more convective and the stable condition is calmer. The diurnal change of stability becomes dramatic. It does not match with the moderate change in Hong Kong. Besides, the mixing height is often below 100m nighttime. It is unreasonable low for an urban area. It causes the sudden shoot up of ground concentration if near-ground sources exist. The shoot up overestimates the actual concentration and is a few times more than the other modelling result. Overall, AERMOD does not perform reasonably well enough.

ADMS is the most reasonable models so far among the four and therefore it is highly recommended. ADMS is an advance Gaussian dispersion model which is believed to be more realistic. The boundary layer condition is not uniform throughout the whole layer by implementation of M-O length scales. Mechanical turbulence dominates the layer near the ground while convective one dominates the upper layer under the unstable condition. Even if it is stable stability, mixing due to wind shear is
still important near ground surface. The diurnal change of stability is moderate and matches with Hong Kong situation.

ADMS possesses features that help better simulation of an urban area. Theoretically, ADMS and AERMOD are based on the same similarly theory. ADMS also suffers from the problem of unreasonably low mixing heights which is 50 meters the least. But ADMS actually is free from this problem by specifying a minimum Monin-Obukhov length. The purpose of the minimum Monin-Obukhov length is to avoid the boundary condition from getting too stable for an urban region. This minimum M-O length implicitly restricts the least value of mixing height at the same time. Hourly mixing height does not below the least value. In real case, urbanized area generates significant amount of heat at nighttime. The excessive heat enhances the vertical mixing and keeps the boundary layer not that stable as rural area. It also induces a mixing layer above the urban area. The features in ADMS exactly simulate the mentioned effect by an urbanized area.

Every parameters fall in reasonable range in ADMS. ADMS allows access to the results of the parameterization generated by the meteorological pre-processor. It provides another pathway to justify the modelling results. Typical parameters are mixing height, M-O length scale, heat flux, surface friction velocity, vertical velocity and etc. Either one of them going wild certainly results in extreme concentration. In the above modelling cases, none of the parameters is reported to be inconsistent with Hong Kong situation. The modelling results of ADMS are considered with high confidence.

However, ADMS has its drawbacks too. It does not perform well in very weak wind or very stable situation. ADMS has the highest allowable wind speed of 0.75m/s. It certainly underestimates the concentration as strong wind is considered in the calculation. Capped M-O length in ADMS restricts the stability from going too stable. If the actual stability goes beyond that limit, ADMS is unable to calculate the concentration accurately. Anyway, Hong Kong is relatively windy and is a highly urbanized are. These two problems are of minor concern in the application on Hong Kong cases.
From previous section, we know that advance models implement recent research atmospheric physics and return with more detail parameters used on calculation, which provides essential information on verifying predicted concentrations. All these new elements and breakthrough in advance models take only a double more runtime than the conventional one, not to mention the machine nowadays are getting more powerful in a short cycle, which means advance models can return results in a shorter time but remains informative as design.

Besides performance, the decision on the prospective model is subject to many other factors. Functionality, popularity, cost and availability of models are put into consideration. No matter which model is chosen, the dispersion models should be handled with extra care.

1. Model performance extensively depends on the input. The concentration of pollutant is sensitive to meteorological data. Try to describe the modelling site, provide the meteorological data as precise as can be.

2. Monthly mean contour or longer time average and

3. Long-term averaging results as well as short-term one should be considered at the same time. Long-term average usually conceals extreme prediction from the audience. Short-term average is the solution for this problem.

4. Modelling results should undergo validation check before interpreting the air quality impact. The check can be done with reference to the available information in hand, results of parameterization in ADMS and AERMOD for instance.

5. Gaussian dispersion model is relatively simple and straight-forward. If a model prediction falls into marginal case around the air quality standard, other more sophisticated dispersion models should be applied for detail analysis.
References

ISC3 Technical Manual

AERMOD Technical Manual

AERMET Technical Manual

ISC-AERMOD View User Manual

ADMS User Manual

ADMS Technical Specification

AUSPLUME User Manual

CALINE4 User Manual

Guidelines on Choice of Models and Model Parameters, HKEPD


Appendix A

Hourly Average Contour at 24th July 2004
At Castle Peak Power Station
Figure 58 Day 206 hour 1 & 2 at the Power Plant
Figure 59 Day 206 hour 3 & 4 at the Power Plant
Figure 60 Day 206 hour 5 & 6 at the Power Plant
Figure 61 Day 206 hour 7 & 8 at the Power Plant
Figure 62 Day 206 hour 9 & 10 at the Power Plant
Figure 63 Day 206 hour 11 & 12 at the Power Plant
Hour 13

ADMS

AERMOD

ISC

AUSPLUME

Hour 14

Figure 64 Day 206 hour 13 & 14 at the Power Plant
Figure 65 Day 206 hour 15 & 16 at the Power Plant
Figure 66 Day 206 hour 17 & 18 at the Power Plant
Figure 67 Day 206 hour 19 & 20 at the Power Plant
Figure 68 Day 206 hour 21 & 22 at the Power Plant
Figure 69 Day 206 hour 23 & 24 at the Power Plant
Appendix B

Hourly Average Contours at 16th January 2003
At Hong Kong International Airport
Hour 1
ADMS

Hour 2

AERMOD

ISC

AUSPLUME

Figure 70 Day 16 hour 1 & 2 at the Airport
Figure 71 Day 16 hour 3 & 4 at the Airport
Figure 72 Day 16 hour 5 & 6 at the Airport
Figure 73 Day 16 hour 7 & 8 at the Airport
Figure 74 Day 16 hour 9 & 10 at the Airport
Figure 75 Day 16 hour 11 & 12 at the Airport
Figure 76 Day 16 hour 13 & 14 at the Airport
Figure 77 Day 16 hour 15 & 16 at the Airport
Hour 17

ADMS

AERMOD

ISC

AUSPLUME

Hour 18

Figure 78 Day 16 hour 17 & 18 at the Airport
Figure 79 Day 16 hour 19 & 20 at the Airport
Figure 80 Day 16 hour 21 & 22 at the Airport
Figure 81 Day 16 hour 23 & 24 at the Airport
Appendix C

Hourly Average Contour at 16\textsuperscript{th} January 2003
At Hong Kong International Airport
ADMS with replaced met data
Hour 1
ADMS

Met replaced ADMS

AERMOD

Hour 2

Figure 82 Day 16 hour 1 & 2 at the Airport
Figure 83 Day 16 hour 3 & 4 at the Airport
Figures 84: Day 16, hour 5 & 6 at the Airport
Figure 85 Day 16 hour 7 & 8 at the Airport
Figure 86 Day 16 hour 9 & 10 at the Airport
Figure 87 Day 16 hour 11 & 12 at the Airport
Figure 88 Day 16 hour 13 & 14 at the Airport
Figure 89 Day 16 hour 15 & 16 at the Airport
Figure 90 Day 16 hour 17 & 18 at the Airport
Figure 91 Day 16 hour 19 & 20 at the Airport
Figure 92 Day 16 hour 21 & 22 at the Airport
Figure 93 Day 16 hour 23 & 24 at the Airport