THESIS

APPLICATION OF CALPUFF MODELING SYSTEM AND EMISSION FACTORS FOR HUMAN HEALTH RISK ASSESSMENT IN HINGRUDE COAL-FIRED POWER PLANT

ICH SIRIPRASERT

GRADUATE SCHOOL, KASETSART UNIVERSITY
2008

THESIS

APPLICATION OF CALPUFF MODELING SYSTEM AND EMISSION FACTORS FOR HUMAN HEALTH RISK ASSESSMENT IN HINGRUDE COAL-FIRED POWER PLANT

ICH SIRIPRASERT

A Thesis Submitted in Partial Fulfillment of
the Requirements for the Degree of
Master of Engineering (Environmental Engineering)
Graduate School, Kasetsart University
2008

Ich Siriprasert 2008: Application of CALPUFF Modeling System and Emission Factors for Human Health Risk Assessment in Hingrude Coal-Fired Power Plant. Master of Engineering (Environmental Engineering), Major Field: Environmental Engineering, Department of Environmental Engineering. Thesis Advisor: Assistant Professor Narumol Vongthanasunthorn, D.Eng. 353 pages.

Increasing number of coal-fired power plants caused by rapid growth of electricity consumption worldwide has drawn a resistance from environmentalists and people concerned with air pollution contributed from these plants. To reduce these problems, EIA is required to be conducted and approved before their construction. However, only a few air pollutants emitted from the plant are commonly investigated in EIA, and human health risk assessment is usually left out of EIA. The main objectives of this study are (1) to identify air pollutants released from a typical coal-fired power plant, (2) to determine the air quality impacts of pollutants released from Hingrude coal-fired power plant using CALPUFF modeling system and U.S. EPA's emission factors, and (3) to calculate human health related risks of air pollutants emitted from Hingrude coal-fired power plant to local people. The study reveals that there are at least 108 pollutants emitted from a typical coal-fired power plant, but only 27 pollutants were tested in CALPUFF modeling system due mainly to availability of U.S. EPA's emission factors of the pollutants. The air quality impacts and most total carcinogenic risks of these pollutants were found acceptable to people in villages near Hingrude coal-fired power plant. However, these pollutants are likely to cause non-carcinogenic effects on these villagers. A possible explanation for this is that only some of the pollutants investigated within this study are considered human carcinogen whereas almost all of them contribute to non-carcinogenic human health related effects. It is therefore suggested that other pollutants emitted from coal-fired power plants, apart from SO_2, NO_2 and PM_{10}, be examined in EIA. Human health risk assessment for these pollutants should also be included within the process of EIA for coal-fired power plant, including Hingrude coal-fired power plant as well.

____________________ ____________________ ___ / ___ / ___

Student's signature Thesis Advisor's signature

ACKNOWLEDGEMENTS

Completing this thesis might be out of question without the support of the author's advisor, Assistant Professor Dr. Narumol Vongthanasunthorn. Therefore, the author would like to express his appreciation and thank her for valuable advice, insight knowledge, and precious time during this research study. Additionally, the author would like to sincerely thank Dr. Suchat Leungprasert as the thesis co-advisor, for his exceptional opinions, comments and advice, and several persons at the Department of Rural Roads, especially Mr. Pisuth Sutthipoon for encouragement and valuable suggestions on how to conduct this research study in general. The author also greatly appreciates Dr. Vanisa Surapipith for supporting the crucial data and practical information, and providing helpful comments on how to use CALPUFF modeling system. Needless to say, the author would like to thank his beloved parents for unlimited support and encouragement throughout this study. Without their understanding, this thesis would not have been done smoothly. Last but not least, the author would like to thank those whom the author does not mention for their support until the research has been done.

Ich Siriprasert
March 2008

TABLE OF CONTENTS

Page

TABLE OF CONTENTS i
LIST OF TABLES ii
LIST OF FIGURES iv
INTRODUCTION 1
OBJECTIVES 4
LITERATURE REVIEW 6
MATERIALS AND METHODS 67
  Materials 67
  Methods 67
RESULTS AND DISCUSSION 79
  Results 79
  Discussion 121
CONCLUSION AND RECOMMENDATION 131
  Conclusion 131
  Recommendation 133
LITERATURE CITED 134
APPENDICES 139
  Appendix A Detailed information on Hingrude coal-fired power plant 140
  Appendix B Detailed information on coal 143
  Appendix C General properties and hazard impacts of 27 air pollutants 154
  Appendix D Three hazard rankings for 27 air pollutants 188
  Appendix E U.S. EPA's alternative models 222
  Appendix F U.S. EPA's emission factors for 27 air pollutants 231
  Appendix G Slope factors and reference doses for 27 air pollutants 234
  Appendix H Ambient air quality standards of U.S. EPA 237
  Appendix I Concentrations of 27 air pollutants at four villages 239
  Appendix J Hourly typical dispersion graphics of NO_2, PM_{10} and SO_2 245

LIST OF TABLES

Table		Page
1	Air pollutants emitted from typical coal-fired power plant	11
2	Origin of air pollutants from coal combustion	14
3	27 selected air pollutants released from coal combustion	16
4	Hazard rankings for selected air pollutants from coal combustion	18
5	Comparison of AERMOD, CALPUFF and ISC3 models	32
6	Data input required by CALPUFF modeling system	48
7	Meteorological observation stations used	70
8	Coordinates for four villages near Hingrude coal-fired power plant	73
9	Ambient air standards of Thailand	75
10	Data input for simulating CALPUFF modeling system	79
11	Calculated emission rates for 27 selected air pollutants	85
12	Average concentrations of SO_2, CO, NO_2 and PM_{10} at four villages	88
13	Maximum 24-hour concentrations of SO_2, CO, NO_2 and PM_{10} at four Villages	89
14	CDIs for 27 pollutants at four villages	93
15	ADIs for 27 Pollutants at four villages	97
16	Carcinogenic risks of 27 pollutants at four villages	100
17	Noncarcinogenic risks of 27 pollutants at four villages	104
18	Total carcinogenic risks at four villages and carcinogenic risk standards	105
19	Total noncarcinogenic risks at four villages and noncarcinogenic risk standards	105
20	Carcinogenic risk ranking for four villages	106
21	Noncarcinogenic risk ranking for four villages	108
22	Final carcinogenic risk ranking	110
23	Final noncarcinogenic risk ranking	110
24	Noncarcinogenic risks of NO_2, PM_{10} and SO_2 at four villages	112
25	Total noncarcinogenic risks of NO_2, PM_{10} and SO_2 at four villages	112
26	Comparison of total noncarcinogenic risks at four villages	113

LIST OF TABLES (Continued)

Appendix Table **Page**

A1 Detailed information on proposed Hingrude coal-fired power plant 140
B1 Typical properties of coal from several countries 147
C1 General properties of 27 selected air pollutants from coal combustion 154
C2 Hazard effects of 27 selected pollutants from coal combustion 157
D1 Toxic hazard value based on threshold limit value 201
D2 Carcinogenic hazard value based on EPA rating 202
D3 Vapor pressure hazard value 203
D4 Flammability and reactivity hazard value by NFPA 205
D5 Corrosivity hazard value under DOT classification 205
D6 Substances with TESs based on ionized forms 214
D7 Toxicity component scoring 215
D8 SC average and cutoffs 218
D9 Exposure status scoring 220
F1 U.S. EPA’s coal combustion emission factors for 27 selected pollutants 232
G1 Slope factors and reference doses for 27 selected air pollutants 234
H1 Ambient air quality standards of U.S. EPA 237
I1 24-hour concentrations of 27 selected pollutants at Ban Khok Ta Hom 239
I2 24-hour concentrations of 27 selected pollutants at Ban Ang Dhong 241
I3 24-hour concentrations of 27 selected pollutants at Ban Nong Ya Plong 242
I4 24-hour concentrations of 27 selected pollutants at Ban Grude 243

LIST OF FIGURES

Figure		Page
1	Proposed location of Hingrude coal-fired power plant	3
2	Electricity production process of typical coal-fired power plant	7
3	Coal combustion processes	7
4	Typical Gaussian plume dispersion of pollutants from an elevated source	24
5	Difference between plume and puff models	40
6	Graphical representation of puff modeling approach	41
7	CALPUFF modeling system elements	47
8	4-step human health risk assessment process	66
9	Procedure for running CALPUFF modeling system	72
10	Locations of four villages near Hingrude coal-fired power plant	73
11	Procedure of research methodologies	78
12	Perspective view of locations of Hingrude coal-fired power plant and four villages	87
13	19th hour dispersion of NO_2 in winter	114
14	18th hour dispersion of NO_2 in summer	115
15	22nd hour dispersion of NO_2 in rainy season	115
16	16th hour dispersion of PM_{10} in winter	116
17	17th hour dispersion of PM_{10} in summer	116
18	19th hour dispersion of PM_{10} in rainy season	117
19	17th hour dispersion of SO_2 in winter	117
20	17th hour dispersion of SO_2 in summer	118
21	24th hour dispersion of SO_2 in rainy season	118
22	21st hour dispersion of NO_2 in rainy season	119
23	22nd hour dispersion of NO_2 in rainy season	120
24	23rd hour dispersion of NO_2 in rainy season	120
25	24th hour dispersion of NO_2 in rainy season	121

LIST OF FIGURES (Continued)

Appendix Figure		Page
A1	Proposed location of Hingrude coal-fired power plant	141
B1	Classification of coal	146
J1	1st hour dispersion of NO_2 in winter	245
J2	2nd hour dispersion of NO_2 in winter	246
J3	3rd hour dispersion of NO_2 in winter	246
J4	4th hour dispersion of NO_2 in winter	247
J5	5th hour dispersion of NO_2 in winter	247
J6	6th hour dispersion of NO_2 in winter	248
J7	7th hour dispersion of NO_2 in winter	248
J8	8th hour dispersion of NO_2 in winter	249
J9	9th hour dispersion of NO_2 in winter	249
J10	10th hour dispersion of NO_2 in winter	250
J11	11th hour dispersion of NO_2 in winter	250
J12	12th hour dispersion of NO_2 in winter	251
J13	13th hour dispersion of NO_2 in winter	251
J14	14th hour dispersion of NO_2 in winter	252
J15	15th hour dispersion of NO_2 in winter	252
J16	16th hour dispersion of NO_2 in winter	253
J17	17th hour dispersion of NO_2 in winter	253
J18	18th hour dispersion of NO_2 in winter	254
J19	19th hour dispersion of NO_2 in winter	254
J20	20th hour dispersion of NO_2 in winter	255
J21	21st hour dispersion of NO_2 in winter	255
J22	22nd hour dispersion of NO_2 in winter	256
J23	23rd hour dispersion of NO_2 in winter	256
J24	24th hour dispersion of NO_2 in winter	257
J25	1st hour dispersion of NO_2 in summer	257
J26	2nd hour dispersion of NO_2 in summer	258

LIST OF FIGURES (Continued)

Appendix Figure **Page**

J27 3rd hour dispersion of NO_2 in summer 258
J28 4th hour dispersion of NO_2 in summer 259
J29 5th hour dispersion of NO_2 in summer 259
J30 6th hour dispersion of NO_2 in summer 260
J31 7th hour dispersion of NO_2 in summer 260
J32 8th hour dispersion of NO_2 in summer 261
J33 9th hour dispersion of NO_2 in summer 261
J34 10th hour dispersion of NO_2 in summer 262
J35 11th hour dispersion of NO_2 in summer 262
J36 12th hour dispersion of NO_2 in summer 263
J37 13th hour dispersion of NO_2 in summer 263
J38 14th hour dispersion of NO_2 in summer 264
J39 15th hour dispersion of NO_2 in summer 264
J40 16th hour dispersion of NO_2 in summer 265
J41 17th hour dispersion of NO_2 in summer 265
J42 18th hour dispersion of NO_2 in summer 266
J43 19th hour dispersion of NO_2 in summer 266
J44 20th hour dispersion of NO_2 in summer 267
J45 21st hour dispersion of NO_2 in summer 267
J46 22nd hour dispersion of NO_2 in summer 268
J47 23rd hour dispersion of NO_2 in summer 268
J48 24th hour dispersion of NO_2 in summer 269
J49 1st hour dispersion of NO_2 in rainy season 269
J50 2nd hour dispersion of NO_2 in rainy season 270
J51 3rd hour dispersion of NO_2 in rainy season 270
J52 4th hour dispersion of NO_2 in rainy season 271
J53 5th hour dispersion of NO_2 in rainy season 271
J54 6th hour dispersion of NO_2 in rainy season 272

LIST OF FIGURES (Continued)

Appendix Figure		Page
J55	7th hour dispersion of NO_2 in rainy season	272
J56	8th hour dispersion of NO_2 in rainy season	273
J57	9th hour dispersion of NO_2 in rainy season	273
J58	10th hour dispersion of NO_2 in rainy season	274
J59	11th hour dispersion of NO_2 in rainy season	274
J60	12th hour dispersion of NO_2 in rainy season	275
J61	13th hour dispersion of NO_2 in rainy season	275
J62	14th hour dispersion of NO_2 in rainy season	276
J63	15th hour dispersion of NO_2 in rainy season	276
J64	16th hour dispersion of NO_2 in rainy season	277
J65	17th hour dispersion of NO_2 in rainy season	277
J66	18th hour dispersion of NO_2 in rainy season	278
J67	19th hour dispersion of NO_2 in rainy season	278
J68	20th hour dispersion of NO_2 in rainy season	279
J69	21st hour dispersion of NO_2 in rainy season	279
J70	22nd hour dispersion of NO_2 in rainy season	280
J71	23rd hour dispersion of NO_2 in rainy season	280
J72	24th hour dispersion of NO_2 in rainy season	281
J73	1st hour dispersion of PM_{10} in winter	281
J74	2nd hour dispersion of PM_{10} in winter	282
J75	3rd hour dispersion of PM_{10} in winter	282
J76	4th hour dispersion of PM_{10} in winter	283
J77	5th hour dispersion of PM_{10} in winter	283
J78	6th hour dispersion of PM_{10} in winter	284
J79	7th hour dispersion of PM_{10} in winter	284
J80	8th hour dispersion of PM_{10} in winter	285
J81	9th hour dispersion of PM_{10} in winter	285
J82	10th hour dispersion of PM_{10} in winter	286

LIST OF FIGURES (Continued)

Appendix Figure **Page**

J83 11th hour dispersion of PM_{10} in winter 286
J84 12th hour dispersion of PM_{10} in winter 287
J85 13th hour dispersion of PM_{10} in winter 287
J86 14th hour dispersion of PM_{10} in winter 288
J87 15th hour dispersion of PM_{10} in winter 288
J88 16th hour dispersion of PM_{10} in winter 289
J89 17th hour dispersion of PM_{10} in winter 289
J90 18th hour dispersion of PM_{10} in winter 290
J91 19th hour dispersion of PM_{10} in winter 290
J92 20th hour dispersion of PM_{10} in winter 291
J93 21st hour dispersion of PM_{10} in winter 291
J94 22nd hour dispersion of PM_{10} in winter 292
J95 23rd hour dispersion of PM_{10} in winter 292
J96 24th hour dispersion of PM_{10} in winter 293
J97 1st hour dispersion of PM_{10} in summer 293
J98 2nd hour dispersion of PM_{10} in summer 294
J99 3rd hour dispersion of PM_{10} in summer 294
J100 4th hour dispersion of PM_{10} in summer 295
J101 5th hour dispersion of PM_{10} in summer 295
J102 6th hour dispersion of PM_{10} in summer 296
J103 7th hour dispersion of PM_{10} in summer 296
J104 8th hour dispersion of PM_{10} in summer 297
J105 9th hour dispersion of PM_{10} in summer 297
J106 10th hour dispersion of PM_{10} in summer 298
J107 11th hour dispersion of PM_{10} in summer 298
J108 12th hour dispersion of PM_{10} in summer 299
J109 13th hour dispersion of PM_{10} in summer 299
J110 14th hour dispersion of PM_{10} in summer 300

LIST OF FIGURES (Continued)

Appendix Figure **Page**

J111 15th hour dispersion of PM_{10} in summer 300
J112 16th hour dispersion of PM_{10} in summer 301
J113 17th hour dispersion of PM_{10} in summer 301
J114 18th hour dispersion of PM_{10} in summer 302
J115 19th hour dispersion of PM_{10} in summer 302
J116 20th hour dispersion of PM_{10} in summer 303
J117 21st hour dispersion of PM_{10} in summer 303
J118 22nd hour dispersion of PM_{10} in summer 304
J119 23rd hour dispersion of PM_{10} in summer 304
J120 24th hour dispersion of PM_{10} in summer 305
J121 1st hour dispersion of PM_{10} in rainy season 305
J122 2nd hour dispersion of PM_{10} in rainy season 306
J123 3rd hour dispersion of PM_{10} in rainy season 306
J124 4th hour dispersion of PM_{10} in rainy season 307
J125 5th hour dispersion of PM_{10} in rainy season 307
J126 6th hour dispersion of PM_{10} in rainy season 308
J127 7th hour dispersion of PM_{10} in rainy season 308
J128 8th hour dispersion of PM_{10} in rainy season 309
J129 9th hour dispersion of PM_{10} in rainy season 309
J130 10th hour dispersion of PM_{10} in rainy season 310
J131 11th hour dispersion of PM_{10} in rainy season 310
J132 12th hour dispersion of PM_{10} in rainy season 311
J133 13th hour dispersion of PM_{10} in rainy season 311
J134 14th hour dispersion of PM_{10} in rainy season 312
J135 15th hour dispersion of PM_{10} in rainy season 312
J136 16th hour dispersion of PM_{10} in rainy season 313
J137 17th hour dispersion of PM_{10} in rainy season 313
J138 18th hour dispersion of PM_{10} in rainy season 314

LIST OF FIGURES (Continued)

Appendix Figure **Page**

J139 19th hour dispersion of PM_{10} in rainy season 314
J140 20th hour dispersion of PM_{10} in rainy season 315
J141 21st hour dispersion of PM_{10} in rainy season 315
J142 22nd hour dispersion of PM_{10} in rainy season 316
J143 23rd hour dispersion of PM_{10} in rainy season 316
J144 24th hour dispersion of PM_{10} in rainy season 317
J145 1st hour dispersion of SO_2 in winter 317
J146 2nd hour dispersion of SO_2 in winter 318
J147 3rd hour dispersion of SO_2 in winter 318
J148 4th hour dispersion of SO_2 in winter 319
J149 5th hour dispersion of SO_2 in winter 319
J150 6th hour dispersion of SO_2 in winter 320
J151 7th hour dispersion of SO_2 in winter 320
J152 8th hour dispersion of SO_2 in winter 321
J153 9th hour dispersion of SO_2 in winter 321
J154 10th hour dispersion of SO_2 in winter 322
J155 11th hour dispersion of SO_2 in winter 322
J156 12th hour dispersion of SO_2 in winter 323
J157 13th hour dispersion of SO_2 in winter 323
J158 14th hour dispersion of SO_2 in winter 324
J159 15th hour dispersion of SO_2 in winter 324
J160 16th hour dispersion of SO_2 in winter 325
J161 17th hour dispersion of SO_2 in winter 325
J162 18th hour dispersion of SO_2 in winter 326
J163 19th hour dispersion of SO_2 in winter 326
J164 20th hour dispersion of SO_2 in winter 327
J165 21st hour dispersion of SO_2 in winter 327
J166 22nd hour dispersion of SO_2 in winter 328

LIST OF FIGURES (Continued)

Appendix Figure **Page**

J167 23rd hour dispersion of SO_2 in winter 328
J168 24th hour dispersion of SO_2 in winter 329
J169 1st hour dispersion of SO_2 in summer 329
J170 2nd hour dispersion of SO_2 in summer 330
J171 3rd hour dispersion of SO_2 in summer 330
J172 4th hour dispersion of SO_2 in summer 331
J173 5th hour dispersion of SO_2 in summer 331
J174 6th hour dispersion of SO_2 in summer 332
J175 7th hour dispersion of SO_2 in summer 332
J176 8th hour dispersion of SO_2 in summer 333
J177 9th hour dispersion of SO_2 in summer 333
J178 10th hour dispersion of SO_2 in summer 334
J179 11th hour dispersion of SO_2 in summer 334
J180 12th hour dispersion of SO_2 in summer 335
J181 13th hour dispersion of SO_2 in summer 335
J182 14th hour dispersion of SO_2 in summer 336
J183 15th hour dispersion of SO_2 in summer 336
J184 16th hour dispersion of SO_2 in summer 337
J185 17th hour dispersion of SO_2 in summer 337
J186 18th hour dispersion of SO_2 in summer 338
J187 19th hour dispersion of SO_2 in summer 338
J188 20th hour dispersion of SO_2 in summer 339
J189 21st hour dispersion of SO_2 in summer 339
J190 22nd hour dispersion of SO_2 in summer 340
J191 23rd hour dispersion of SO_2 in summer 340
J192 24th hour dispersion of SO_2 in summer 341
J193 1st hour dispersion of SO_2 in rainy season 341
J194 2nd hour dispersion of SO_2 in rainy season 342

LIST OF FIGURES (Continued)

Appendix Figure **Page**

J195 3rd hour dispersion of SO_2 in rainy season 342
J196 4th hour dispersion of SO_2 in rainy season 343
J197 5th hour dispersion of SO_2 in rainy season 343
J198 6th hour dispersion of SO_2 in rainy season 344
J199 7th hour dispersion of SO_2 in rainy season 344
J200 8th hour dispersion of SO_2 in rainy season 345
J201 9th hour dispersion of SO_2 in rainy season 345
J202 10th hour dispersion of SO_2 in rainy season 346
J203 11th hour dispersion of SO_2 in rainy season 346
J204 12th hour dispersion of SO_2 in rainy season 347
J205 13th hour dispersion of SO_2 in rainy season 347
J206 14th hour dispersion of SO_2 in rainy season 348
J207 15th hour dispersion of SO_2 in rainy season 348
J208 16th hour dispersion of SO_2 in rainy season 349
J209 17th hour dispersion of SO_2 in rainy season 349
J210 18th hour dispersion of SO_2 in rainy season 350
J211 19th hour dispersion of SO_2 in rainy season 350
J212 20th hour dispersion of SO_2 in rainy season 351
J213 21st hour dispersion of SO_2 in rainy season 351
J214 22nd hour dispersion of SO_2 in rainy season 352
J215 23rd hour dispersion of SO_2 in rainy season 352
J216 24th hour dispersion of SO_2 in rainy season 353

APPLICATION OF CALPUFF MODELING SYSTEM AND EMISSION FACTORS FOR HUMAN HEALTH RISK ASSESSMENT IN HINGRUDE COAL-FIRED POWER PLANT

INTRODUCTION

In today's world, it is no doubt that energy has become a basic necessity in our lives; electrical appliances that we use, vehicles that we drive and even machines used in factories all require energy to function. With advanced and ongoing technology development, even more energy-consuming items will be invented or developed for use. There are basically many forms of energy available for use, such as electricity, thermal energy, wind energy, heat energy, mechanical energy and so on. Amongst these forms of energy, electricity is one of the most widely used forms worldwide. Owing to availability of coal, associated costs and simplicity of technology available, most electricity is currently produced from coal-fired power plants, with the rest being generated from natural gas and nuclear power plants, and other energy resources, such as solar power, wind power, hydro-power, etc. For example, more than 50% of electricity used in the USA annually comes from coal-fired power plants (Roger, 2006).

Despite its importance mentioned above, the operation of a coal-fired power plant generally provides environmental problems and adverse effects on human health, reflecting that more coal-fired power plants mean more pollution. Because of this, it is now obligatory in many countries, e.g. Thailand, to conduct environmental impact assessment (EIA) for a coal-fired power plant, prior to its construction, to ascertain whether its future released environmental impacts exceed the safe standard values or not. However, the construction of a new plant in many countries, including Thailand, still encounters resistance from local people and environmentalists due mainly to future air pollution caused by these plants even though the EIA has been approved already. Such an occurrence raises questions as to whether there are other air pollutants released from coal-fired power plant, which have never been investigated in EIA (Only sulfur dioxide, oxides of nitrogen and particulate matter are examined in

EIA.), and whether these air pollutants are likely to cause negative impacts on local people, if they exist.

Consequently, there is a need for research to investigate and identify the existence of these air pollutants, and then predict their air quality impacts on local people. This is where this study originates from. In determining the air quality impacts of these air pollutants, there are presently a number of methods available. Amongst these options, an air dispersion model is an attractive option to use for this research because not only it is accepted and widely used by relevant government agencies, organizations and private companies worldwide, but also its operation cost is small in comparison with other methods e.g. field sampling/monitoring and laboratory tests (Panich and Panich, 2001). Human health risk assessment for these air pollutants also needs to be carried out to be able to estimate their human health related risks to local people, so that appropriate/effective risk prevention measure can be developed for each of the risks that are not acceptable afterwards.

The construction of Hingrude coal-fired power plant in Prachuap Khiri Khan, Thailand has been the serious issue in dispute for the last ten years; local people have resisted its construction with the reason that it would deteriorate the environment and human health, even though its EIA has been approved for a long time. Hence, it is appropriate to select and use Hingrude coal-fired power plant in this study as an example of a typical coal-fired power plant for estimating human health risk and predicting air quality impacts of the air pollutants emitted from the plant.

As Hingrude coal-fired power plant has not been constructed yet, actual emission rates of the pollutants released cannot be measured. Instead, U.S. EPA’s coal combustion emission factors are used in this study to estimate their potential emission rates, which are the key data input for air dispersion model. Additionally, because the plant is located near coastal area, CALPUFF modeling system (approved by U.S. EPA as a preferred/recommended air quality model) specifically designed for predicting pollutant dispersion over water and calculating air quality impacts in coastal area is used as an air dispersion model in this study. The following pictures show the proposed location of Hingrude coal-fried power plant in Thailand (see appendix A for further information on proposed Hingrude coal-fired power plant).

Figure 1 Proposed location of Hingrude coal-fired power plant

OBJECTIVES

The main objectives of this research study are therefore as follows:

1. To identify air pollutants released from a typical coal-fired power plant,

2. To determine the air quality impacts of air pollutants released from Hingrude coal-fired power plant using CALPUFF modeling system and U.S. EPA's emission factors,

3. To calculate and rank human health related risks of air pollutants emitted from Hingrude coal-fired power plant to local people

Scope of Study

The scope of this study covers the following.

1. Investigation into characteristics and operation processes of coal-fired power plants worldwide to discover air pollutants released from coal combustion processes. The environmental impacts and human health related effects of these air pollutants as well as their origins and hazard ranking systems were also studied to find out which pollutant tend to contribute more hazards.

2. Study of U.S. EPA's recommended air dispersion models currently available for use, their features, advantages and disadvantages, characteristics of Hingrude coal-fired power plant (proposed stack height, stack diameter, exit temperature and exit velocity) and its location included within EIA, to select the most appropriate air dispersion model for predicting air quality impacts of Hingrude coal-fired power plant.

3. Collection, examination and preparation of information required for running an air dispersion model selected (CALPUFF modeling system), such as

meteorological data for the year 2006 (wind speed, wind direction, relative humidity, air pressure, precipitation rate, mixing height and temperature), geophysical data for the area in which proposed Hingrude coal-fired power plant is located (land use and terrain surface elevation) and U.S. EPA's emission factors for air pollutants emitted from a typical coal-fired power plant. In this study, required meteorological data for the year 2006 were collected from meteorological observations stations (nearest Hingrude coal-fired power plant) of the Thai Meteorological Department, Pollution Control Department and Geo-Informatics and Space Technology Development Agency whereas necessary U.S. EPA's emission factors were gathered from U.S. EPA website.

4. Collection and investigation of information needed to conduct human health risk assessment e.g. slope factors, reference doses, exposure pathways, exposure frequency and exposure duration of air pollutants released from Hingrude coal-fired power plant. In this research, slope factors and reference doses of the air pollutants were gathered from several professional websites and textbooks with the rest being collected from EIA report for Hingrude coal-fired power plant.

5. Execution of CALPUFF modeling system to predict the dispersion and concentrations of the air pollutants emitted from Hingrude coal-fired power plant in 2006. Ambient air standards of Thailand were collected and used to determine the air quality impacts of these air pollutants on surrounding villages by comparing them with the concentration of the pollutants obtained from the model.

6. Calculation and ranking of human health related risks of these air pollutants to local people residing in villages near Hingrude coal-fired power plant in order to determine whether carcinogenic and non-carcinogenic risks of the air pollutants emitted are acceptable, and which air pollutants contribute to the highest risks.

LITERATURE REVIEW

1. Coal Combustion Process of Typical Coal-Fired Power Plant

Coal, a fossil fuel or black solid combustible substance formed by the partial decomposition of vegetable matter without access to air, is second only to oil as an energy source in the world. Approximately 70% of the world's coal production is used to generate 40% of the world's electricity, 12% is made into coke used to produce 70% of the world's steel, and the remaining 18% is used for other industrial and domestic purposes. See appendix B for further information on coal.

To produce electricity in a coal-fired power plant (the most common technology in electricity generation today), coal is crushed into a fine powder in a grinding mill. The pulverized coal is then blown into the combustion chamber (furnace) of a boiler where it is burned at high temperature. The heat produced by combustion is used to covert water contained in tubes lining the furnace into steam. This high-pressure steam is passed into a turbine containing thousands of propeller-like blades. The expanding steam hits these blades, causing the turbine shaft to rotate at high speed. At the end of the turbine shaft is a generator, consisting of a magnet and copper wire coils. Electricity is generated when the magnet is rapidly rotated in the coils. After passing through the turbine chamber, the steam is condensed and returned to the boiler to be heated once again (Howard, 1996). The following picture illustrates a coal-into-electricity process of a typical coal-fired power plant.

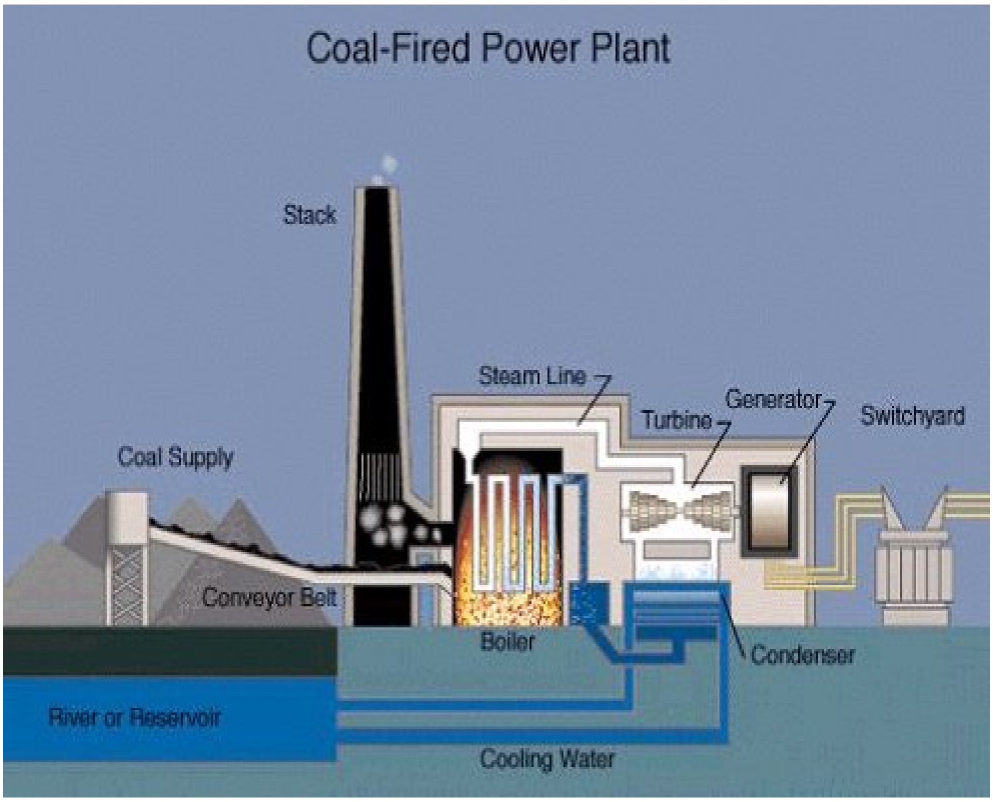


Figure 2 Electricity production process of typical coal-fired power plant
Source: Roger (2006)

During combustion in a boiler of a coal-fired power plant, coal particles undergo four main steps as shown in the figure below.

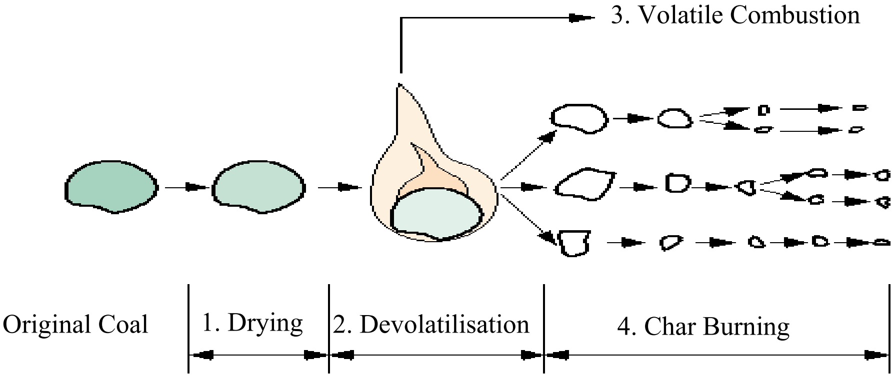


Figure 3 Coal combustion processes
Source: Carpenter *et al*. (2007)

1.1 Drying

Drying which starts once a coal particle enters the furnace, is a heat transfer-limited process that is influenced by the furnace temperature, and the particle size, moisture content and porosity of the coal. On completion of drying, the particle is further heated to the pyrolysis temperature. The heating rate differs significantly between different types of laboratory experiments and between different types of burners, as well as being highly dependent on the coal-particle size. As a result of drying and heating, the particle shrinks, with a reduction in volume that is related to the initial moisture content and the type of fuel. The process may also lead to a reduction in the pore size, internal cracking or particle breakup.

1.2 Devolatilisation

Devolatilisation of coal starts typically at 450–500°C. It produces non-condensible light gases, tar and a residual char. The tar is subsequently converted to soot particles. During devolatilisation, coals exhibit various degrees of bubbling and swelling to form chars of different structures. The volatile yield increases with deceasing coal rank and with increasing temperature, soak time and heating rate. Generally, bituminous coals yield comparatively larger amounts of tar than other coals, whilst lower-rank coals release less tar but larger amounts of light gases. However, some studies have shown no clear correlation between the tar yield and the coal rank. The relative yields of gaseous species also seem to depend on the type of coal and the pyrolysis conditions.

A number of approaches have been developed to model the devolatilisation process. These models can be divided into two groups: empirical global kinetic models and more comprehensive computer-based network models. Global kinetic models use the ultimate volatile yield as an input parameter, to determine the volatile yield as a function of the devolatilisation time. They are relatively simple but are restricted to a particular coal and combustion condition. Network models are based on a structural description of the coal, and allow for predictions of the volatile yield, rate of evolution and volatile composition. Generally, they are more complicated and can be applied to a wide range of coals and process conditions.

1.3 Volatile oxidation

Volatile Oxidation occurs when volatiles are released from the coal particle. The volatiles react with oxygen in the air surrounding the particle, producing CO_2 and H_2O. The reaction is rapid and, therefore, has a negligible effect on the overall combustion time. However, it is important with respect to NO_x formation.

Global oxidation kinetics have been used to predict the reaction rate between volatiles and oxygen. This approach assumes that the volatiles are represented as a single species and that the combustion rate is controlled by mixing with oxygen. However, this results in inaccurate predictions. A more advanced approach is to use the measured or computed volatile species as the input into a flamelet model to calculate the reaction, which allows the modeling of major species oxidation and NO_x formation to be undertaken. Generally, however, there is still only limited knowledge about the processes involved in volatiles oxidation.

1.4 Char oxidation

Char oxidation is a slow process, thus dominating the total burning time of a coal particle. It involves the oxidation of carbon to carbon monoxide (CO) or carbon dioxide (CO_2) at the particle surface. While oxidation to CO_2 dominates at low temperatures, oxidation to CO becomes important at high temperatures, and the direct formation of CO_2 at the char surface is negligible. Hence, the main carbon oxidation becomes a two-step reaction, with the CO being subsequently oxidized to CO_2 away from the char particle.

Char oxidation is controlled by the rate of oxygen diffusion to the particle, by the rate of chemical reaction, or by a combination of these. There are three reaction zones, with limits that are determined by which of these mechanisms provides the principal constraint on the reaction rate. At low temperatures, char oxidation is controlled b y the chemical-reaction rate. At moderate temperatures, both the rates of chemical reaction and oxygen pore diffusion are important, whilst at high temperatures, oxygen diffusion to the particle surface becomes dominant (Carpenter *et al*., 2007).

2. Air Emissions of Typical Coal-Fired Power Plant

Burning coal for power is an inherently polluting process; it typically involves air emission (air pollutants emitted from a plant), soil emission (solid waste as a byproduct of combustion e.g. bottom ash) and water emission (waste effluent from coal combustion). The cumulative impact of all of these effects is worldwide magnified by the enormous quantities of coal burn each year (6,500 million tons approximately). Amongst these three, a coal-fired power plant is a major source of air pollution, such as smog, global warming and acid rain, which contribute to detrimental effects on human health and the environment (Keating, 2001). For instance, in an average year, a typical coal-fired power plant generates the following criteria air pollutants.

2.1 10,000 tons of sulfur dioxide. Sulfur dioxide (SO_2) is the main cause of acid rain, which damages forests, lakes and buildings.

2.2 10,200 tons of nitrogen oxide. Nitrogen oxide (NO_x) is a major cause of smog, and also a cause of acid rain.

2.3 3.7 million tons of carbon dioxide. Carbon dioxide (CO_2) is the main greenhouse gas, and is the leading cause of global warming.

2.4 500 tons of small particles. Small particulates (PM_{10}) are a health hazard, causing lung damage.

2.5 720 tons of carbon monoxide. Carbon monoxide (CO) is a poisonous gas and contributor to global warming.

2.6 Unidentified amount of toxic heavy metals/trace elements e.g. cadmium, lead, arsenic and beryllium. These pollutants are a public health concern because, at sufficient exposure levels, they adversely affect human health, such as cancer, birth defect, brain and immune system damage, respiratory problems, malfunction of some organisms and other ailments.

In addition to the criteria air pollutants mentioned above, air emissions from the combustion of coal include many other pollutants. Several observations and tests have been done at coal-fired power plants in the USA in an effort to solve the mystery of which air pollutants are released from coal combustion by using some equipment (e.g. gas chromatography and mass spectrometry) to extract components from coal combustion flue gas. Around 108 air pollutants have been so far identified in air emission from a typical coal-fired power plant (Markuszewski and Blaustein, 1986). These 108 air pollutants are divided into five groups as shown in the table below.

Table 1 Air pollutants emitted from typical coal-fired power plant

Types of Pollutants	Number of Pollutants	Air Pollutants Emitted from Typical Coal-Fired Power Plant
Dioxin and Furan	14	2,3,7,8-TCDD, TOTAL TCDD, TOTAL PeCDD, TOTAL HxCDD, TOTAL HpCDD, TOTAL OCDD, 2,3,7,8-TCDF, TOTAL TCDF, TOTAL PeCDF, TOTAL HxCDF, TOTAL HpCDF, TOTAL OCDFd, TOTAL CDD and TOTAL CDF
Metal	17	antimony, arsenic, barium, boron, beryllium, chromium, cadmium, cobalt, copper, lead, manganese, magnesium, mercury, nickel, selenium, tin and zinc

Table 1 (Continued)

Types of Pollutants	Number of Pollutants	Air Pollutants Emitted from Typical Coal-Fired Power Plant
Polycyclic Aromatic Hydrocarbons (PAHs)	15	biphenyl, acenaphthylene, anthracene, benz(a)anthracene, benzo(b,j,k)fluoranthene, benzo(g,h,i)perylene, chrysene, fluoranthene, fluorine, indeno(1,2,3-cd)pyrene, phenanthrene, pyrene, 5-methyl chrysene, benzo(a)pyrene and naphthalene
Organic	51	acetaldehyde, acetophenone, acrolein, benzyl-chloride, bis(2-ethyl-hexyl-phthalate), bromoform, 2-chloroacetophenone, chlorobenzene, cumene, cyanide, 1,3-dichloropropylene, dibutry phthalate, n-nitroso dimethylamine, 2,4-dinitro-toluene, dimethyl sulfate, ethyl benzene, ethyl chloride, ethylene dichloride, ethylene dibromide, ethylidene dichloride, formaldehyde, hexachlorobutadiene, hexachloro-ethane, hexane, isophorone, methyl bromide, methyl chloride, methane, methyl hydrazine, methyl ethyl ketone, methyl methacrylate, methyl tert butyl ether, methylene chloride, phenol, propion-aldehyde, propylene dichloride, 1,1,2,2-tetrachloro-ethane,

Table 1 (Continued)

Types of Pollutants	Number of Pollutants	Air Pollutants Emitted from Typical Coal-Fired Power Plant
Organic (Continued)		tetrachloro-ethene, styrene, toluene, 1,1,1-trichloro-ethane, 1,1,2-trichloro-ethane, trichloroethene, vinyl acetate, vinyl chloride, phenol, cyanide, benzene, carbon tetrachloride, chloroform, xylene
Others	11	Ammonia, chlorine, carbon dioxide, carbon monoxide, hydrogen chloride, hydrogen fluoride, hydrogen sulfide, oxides of nitrogen (e.g. nitrogen dioxide, nitric oxide), PM_{10}, sulfur dioxide and sulfuric acid

Source: Merrich (1984); Markuszewski and Blaustein (1986); Berkowitz (1994); Keating (2001)

The identified air pollutants shown in the above table can also be divided into three main categories according to their origins (how they originate from coal combustion.) as can be seen in Table 2.

Table 2 Origin of air pollutants from coal combustion

Air Pollutants Emitted from Coal Combustion	
Groups of Air Pollutants	**Origins of Air Pollutants**
Metallic chemical elements/metalloids and particulate matter (e.g. antimony, barium, cadmium, copper, lead, nickel, PM_{10}, selenium, and zinc)	They are all trace elements found in coal in different proportion. During coal combustion, some minerals are fragmented and released as fine particles with the others being emitted as vapor; some of which will subsequently condense to produce small particles in flue gases. Some of vapor products also tend to react with oxygen and others to form gaseous compounds or ions e.g. sulfide and carbonate.
PAHs (e.g. anthracene, benzo(a)pyrene, naphthalene and pyrene)	They are a class of organic compounds that are contained in the volatile matter evolved from coal at high temperature. Each of them is generally formed during incomplete coal combustion at different temperature range e.g. 300-600°C for benzo(a)pyrene and 170-230°C for naphthalene. Most of them are released into the atmosphere as vapor phase component of the combustion gases, with the rest being condensed onto fine particles in flue gases.

Table 2 (Continued)

Air Pollutants Emitted from Coal Combustion	
Groups of Air Pollutants	**Origins of Air Pollutants**
Trace Gases (e.g. carbon dioxide, hydrogen chloride, cyanide, nitrogen oxides, sulfur dioxide, VOCs (such as benzene, phenol and styrene))	They were initially either major or minor organic elements in coal (e.g. carbon, sulfur, chlorine and nitrogen). During combustion, these elements are converted into gaseous products and/or ions, and then are further reacted with elements/compounds to form toxic gases/ vapors) For instance, most sulfur element contained in coal at high temperature converted into sulfur dioxide gas which will then react with oxygen to form sulfur trioxide. If sulfur trioxide reacts with water in the atmosphere, toxic sulfuric acid will come out as the result of the reaction. Another example is hydrogen chloride. Chlorine gas (Cl_2) released from coal combustion reacts with hydrogen gas (H_2) forming toxic hydrogen chlorine gas.

Source: Merrich (1984); Markuszewski and Blaustein (1986); Berkowitz (1994); Keating (2001); Carpenter *et al* (2007)

Nonetheless, U.S. EPA's emission factors, slope factors (SF) and/or reference doses (RfD) for many of the air pollutants found above are not available. For instance, slope factors and reference doses for carbon dioxide and sulfuric acid are not available whereas U.S. EPA's coal combustion emission factors for tin, nitric oxide, hydrogen sulfide have not been developed. This means that human health risk assessment for these pollutants cannot be done. Some of the air pollutants, e.g. styrene and formaldehyde, also have a very short half life making them not applicable to air dispersion model. Therefore, these air pollutants were ruled out, and as a result only 27 pollutants were selected and tested in air dispersion model. These selected pollutants covering many types of chemicals (volatile organic compounds, polycyclic aromatic hydrocarbons, metals, etc.) are shown in the table below.

Table 3 27 selected air pollutants released from coal combustion

Number of Emitted Pollutants	Air Pollutants Emitted from Coal Combustion
27 pollutants	ammonia, antimony, arsenic, barium, benzene, benzo(a)pyrene, beryllium, carbon tetrachloride, cadmium, chloroform, carbon monoxide, cobalt, copper, chromium, 2,3,7,8-TCDD, hydrogen chloride, lead, manganese, mercury, naphthalene, nickel, nitrogen dioxide, PM_{10}, selenium, sulfur dioxide, vinyl chloride and xylene

As concern about the possible negative impacts of a typical coal-fired power plant is associated mainly with potential health & environmental hazards arising from the dispersion of coal combustion residues and gaseous byproducts released from a plant, the environmental and health hazards of these air pollutants need to be ascertained (see appendix C for general properties, and environmental and health-related effects of the 27 selected air pollutants released from coal combustion).

3. Hazard Ranking of Air Pollutants from Coal Combustion

In order to determine the level of the impacts of the air pollutants from coal combustion, it is necessary to rank these air pollutants in terms of their hazards. There are currently a number of hazard ranking systems for pollutants/substances available worldwide; three of which were developed by renowned organizations, and they have been used by many international organizations for reference purposes. These three include **NPI ranking** by National Pollution Inventory (NPI) under Australian Government, **IRCH ranking** by the Indiana Clean Manufacturing Technology and Safe Materials Institute at Purdue University in the USA, and **CERCLA ranking** by the U.S. EPA and the Agency for Toxic Substances and Disease Registry (ATSDR), federal public health agency of the U.S. Department of Health and Human Services.

These three ranking systems are not only developed by different organizations, but are also derived from distinct criterion. NPI ranking originates from the combination of health hazards and environmental hazards of the pollutants whereas worker exposure hazards and environmental hazards of pollutants are used to set up IRCH ranking. As for CERCLA ranking, occurrence frequency, toxicity and exposure hazard are used together to calculate total hazard score for ranking the pollutants (Agency for Toxic Substances and Disease Registry [ATSDR], 2005; Clean Manufacturing Technology Institute [CMTI], 2007; National Pollutant Inventory [NPI], 2007).

Consequently, both NPI ranking and IRCH ranking must be considered together for evaluating the degree of the environmental hazards of pollutants whilst IRCH ranking and CERCLA ranking both tend to indicate the level of exposure hazards of pollutants. Additionally, NPI ranking and CERCLA ranking can be used together to represent the significant of human hazards of the pollutants (see appendix D for more details on NPI ranking, IRCH ranking and CERCLA ranking). These hazard rankings for selected air pollutants emitted from a typical coal-fired power plant are provided in the table below.

Table 4 Hazard rankings for selected air pollutants from coal combustion

Air Pollutant	NPI Rank	IRCH Rank	CERCLA Rank
Ammonia	45	446	156
Antimony	84	739	222
Arsenic	10	184	1
Barium	-	1053	109
Beryllium	76	51	40
Cadmium	6	132	8
Carbon Monoxide	3	-	188
Chromium	2	134	77
Cobalt	30	509	50
Copper	40	204	133
2,3,7,8-TCDD	-	226	73
Hydrogen Chloride	-	81	-
Lead	11	122	2
Manganese	75	464	115
Mercury	35	231	3
Nickel	54	145	55
Nitrogen Dioxide	1	272	302
Benzo(a)pyrene	-	239	9
Naphthalene	-	215	78
PM10	7	-	-
Selenium	85	453	147
SO_2	4	688	317
Benzene	14	18	6
Carbon Tetrachloride	-	36	46
Chloroform	66	90	11
Vinyl Chloride	65	17	4
Xylene	9	309	59

Source: ATSDR (2005); CMTI (2007); NPI (2007)

From the above table, it can be seen that some pollutants have a top rank in only one or two ranking systems, and a few are ranked high in all ranking systems with the remaining being ranked low or medium in all three rankings. For instance, arsenic and benzene has high ranks in all the three ranking systems indicating that it tends to contribute to high degree of environmental hazards, health hazards and exposure hazards whereas some pollutants, e.g. manganese, are ranked very low in all three rankings representing its low health, environmental and exposure hazards. Cadmium, mercury and lead can be seen as an example of pollutants top ranked in NPI and CERCLA rankings reflecting that their human health related impacts are potentially significant. Being ranked very high in IRCH and CERCLA rankings, some pollutants, such as beryllium, vinyl chloride and chloroform, tend to have high potential for human exposure. Pollutants ranked high in NPI and IRCH rankings, such as nitrogen dioxide, are likely to cause serious environmental problems.

Because there are no rankings for some pollutants in above ranking systems, e.g. barium and hydrogen chloride, and each of the above rankings is derived from the combination of various parameters, e.g. toxicity, exposure frequency, potential for human exposure, environmental effects, etc., the environmental, health and exposure hazard levels of pollutants drawn from these three rankings could contain some error.

Essentially, the hazards of these air pollutants may vary over time, space and place, from short-term episodes of coal dust blown from a plant to the long-term global dispersion of mercury, to climate change, because of several key factors like geology, demographics and climate. Additionally, the impacts are heavily dependent upon the quantities of each of the air pollutants released from a plant, operation of combustion process, types of coal, coal composition and air pollution control equipment used in a plant (Keating, 2001).

As air dispersion model is used in this study to determine the air quality impacts of the air pollutants emitted from coal-fired power plant on local people residing in villages near the plant, it is necessary to investigate approved air dispersion models currently available for use in order to select the model most suitable for conducting this research study.

4. Air Dispersion Model

Air dispersion model is referred to a tool utilized to predict the potential air quality impact of a proposed source on the local environment through computer simulation based upon mathematical formulations for characterizing the atmospheric process that disperse a pollutant emitted from a source of interest (Robert and Robert, 1999). In other words, it is a computer program or a series of mathematical equations used to simulate the transport, diffusion, chemical transformation and physical interactions of pollutants in the atmosphere with the typical solutions being expressed as concentrations for some time period at “receptor” locations.

In order to be able to calculate the concentration of a pollutant of interest, air dispersion models require certain input of data which typically includes meteorological conditions (e.g. wind speed and wind direction, the amount of atmospheric turbulence or stability class and the ambient air temperature), characteristics of emission source (e.g. source location and height, source vent stack diameter and exit velocity), local topography of the source location and the receptor location, and the location, height and width of any obstructions (e.g. buildings or other structures) in the path of the emitted gases (Hall, 2005).

The model can provide information about pollutant impacts on the areas most influenced by emissions from a specific source; not only is it typically used to determine whether existing or proposed new industrial facilities are or will be in compliance with national ambient air quality standards, but it is also used to assist in the design of effective control strategies to reduce emissions of harmful air pollutants. Therefore, it is important to governmental agencies tasked with protecting and managing the ambient air quality, and is considered a potent tool in making a variety of air quality decisions which are based on the air quality expected under a range of possible scenarios (Hall, 2005).

There is currently an array of air dispersion models that have been used in different jurisdictions around the world to handle a wide range of modeling conditions. Generally, air dispersion models can be divided into a number of categories, depending upon what sort of criteria is used in classification, for instance, model characteristics, model complexity, model function, model application, accuracy of the result, mathematical equations used and amount of data input requirements (Godish, 2004).

Air dispersion models can be essentially classified into three main groups according to level of model sophistication (Idriss, 2003). These groups are listed below.

4.1 Simple dispersion model (screening model)

This first level consists of relatively simple estimation techniques that generally use preset, worst-case meteorological conditions to provide conservative estimates of the air quality impact of a specific source, or source category. The models cannot be applied to provide long-term (eight-hour, daily, seasonal, annual) average concentrations. These are called screening techniques or screening models. The aim of this technique is to eliminate the need of more detailed modeling for the sources that clearly will not cause or contribute to ambient concentrations in excess of either the National Ambient Air Quality Standards (Hall, 2005).

4.2 Sophisticated dispersion model (refined model)

The second level is comprised of the analytical techniques that provide more detailed treatment of physical and chemical atmospheric processes, require more detailed and precise input data, and provide more specialized concentration estimates (Idriss, 2003). They require geophysical data, such as terrain and surface roughness, user defined receptors, and a sequential hourly time series of meteorological data. The output can include both short-term (one-hour) and long-term (multiple hour, daily, seasonal, annual) average concentrations at every receptor location. As a result, such models provide a more refined and, at least theoretically, a more accurate estimate of source impact than what screening models give. These are called refined models (Ministry for the Environment of New Zealand, 2004).

4.3 Highly sophisticated dispersion model (advanced model)

The advanced models, sometimes called photochemical models, include formulations that describe such processes (meteorology, emissions and chemistry) in a very comprehensive manner. Such models address building downwash and complex terrain. Consequently, the advanced models are very resource intensive. Due to the resources required, advanced models are typically applied for selected situations (e.g. hour by hour over a few days). Some considerable expertise is required to run and interpret the results of these models (Idriss, 2003).

Sometimes, the dispersion model is broken into only two broad classes: screening and refined modeling. The use of a screening model followed, as appropriate, by a more refined analysis (a refined or advanced model) is always desirable. Nevertheless, there are situations where the screening techniques are practically and technically the only viable option for estimating source impact. In such cases, an attempt should be made to acquire or improve the necessary data bases and to develop appropriate analytical techniques (Robert and Robert, 1999).

5. Air Dispersion Model

According to model complexity, mathematical equations used and assumption of characteristics of pollutant dispersion, air dispersion models are often grouped into two categories as shown below (Arthur, 1976).

5.1 Gaussian plume model

Having been used in the USA since the mid-1960s, Gaussian plume model is considered as a widely-used, well-understood, easy-to-apply and internationally-approved computational approach to calculating the concentration of a pollutant at a certain point (Panich and Panich, 2001). It is basically a group of formulae based on the assumption of steady-state conditions. That is, the Gaussian-plume dispersion formulae do not depend on time, although they do represent an ensemble time average. The meteorological conditions are assumed to remain constant during the dispersion from source to receptor, which is effectively instantaneous. Emissions and meteorological conditions can vary from hour to hour but the model calculations in each hour are independent of those in other hours. Owing to this mathematical derivation, it is common to refer to Gaussian plume models as steady-state dispersion models. In practice, however, the plume characteristics do change over time, because they depend on changing emissions and meteorological conditions. Steady-state models calculate concentrations for each hour from source data and meteorological conditions that are uniform across the modeling domain. Thus, they simulate hourly-average concentrations (Arthur, 1976).

This model basically describes the transport and mixing of the pollutants by assuming that plume spread, and dispersion of pollutants within it, results from molecular diffusion, and because of diffusion, pollutant concentrations in both the horizontal and vertical plume dimensions are distributed normally in bell-shaped curve (Hall, 2005). Below is a picture showing the Gaussian distribution of concentrations in the horizontal and vertical directions with the maximum concentration at the center of the plume.

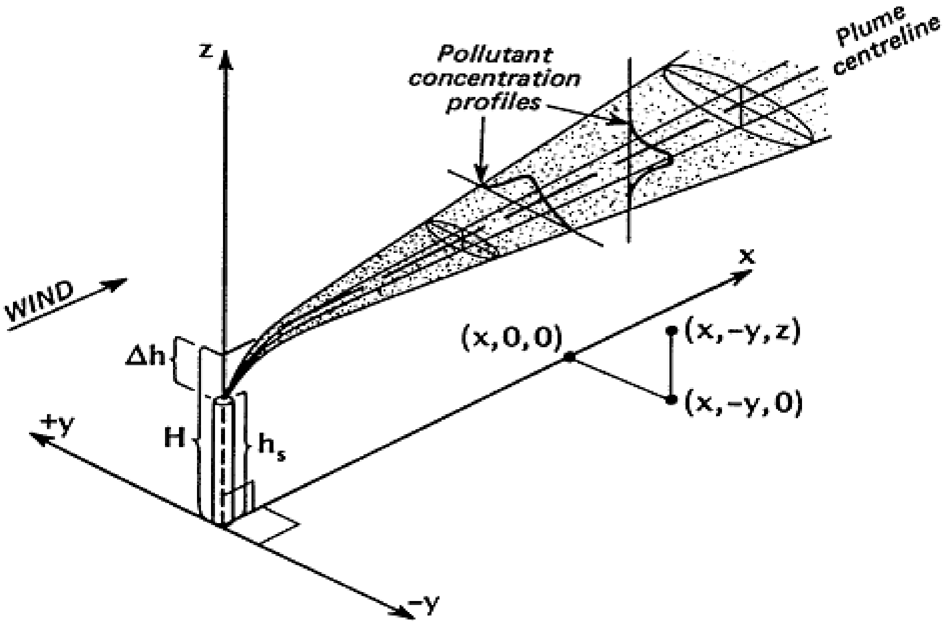


Figure 4 Typical Gaussian plume dispersion of pollutants from an elevated source
Source: Ministry for the Environment of New Zealand (2004)

5.2 Advanced model

Although Gaussian plume models are commonly used in the USA and other countries worldwide for regulatory impact assessments, other less restrictive dispersion models called advanced models are available. These have been in use for scientific research for decades, and are now beginning to enter the regulatory arena. Their use avoids most of the limitations associated with steady-state models. Although their demands on resources (human, computational and data) are far higher than those of Gaussian plume models, computer power is also increasing rapidly, making this aspect less of an issue. However, the use of advanced models does involve much greater meteorological input data demands (Arthur, 1976). Advanced dispersion models may be divided into three groups depending on the way the air pollutants are represented by the model, as listed below (Ministry for the Environment of New Zealand, 2004).

5.2.1 Particles

Pollutant releases, especially those from point sources, are often represented by a stream of particles (even if the pollutant is a gas), which are transported by the model winds and diffuse randomly according to the model turbulence. Particle models are computationally expensive, needing at least 105 particles to represent a pollutant release, but may be the best type to represent pollutant concentrations close to the source.

5.2.2 Puffs

Pollutant releases can also be represented by a series of puffs of material which are also transported by the model winds. Each puff represents a discrete amount of pollution, whose volume increases due to turbulent mixing. Puff models are far less computationally expensive than particle models, but are not as realistic in their description of the pollutant distribution. However, they are often more than adequate, and are used for regulatory purposes.

5.2.3 Grid points

Pollutant distributions are represented by concentrations on a three-dimensional grid of points. This is the cheapest formulation computationally, but difficulties arise when the scale of the pollutant release is smaller than the grid point spacing. This method is commonly used for airshed modeling, and the simulation of chemical transformations is most straightforward in a grid model.

Efforts to increase computational efficiency while still retaining a realistic description of pollutant dispersion mean that many models are a combination of the above-mentioned types. For example, the 'PARTPUFF' approach represents the pollutants as Gaussian puffs in the horizontal and particles in the vertical, particle models usually convert particles to a gridded distribution when the particles have dispersed sufficiently, and grid point models often represent sub-grid-scale releases as particles or puffs (Ministry for the Environment of New Zealand, 2004).

6. U.S. EPA's Air Dispersion Model

There have been a number of air dispersion models available and/or accepted for use in many countries worldwide. Many of these were developed and/or accepted by the U.S. EPA, for use in managing ambient air quality in the USA. Currently, the U.S. EPA has approved a number of models for regulatory application, and lists them in Appendix A of the Guideline on Air Quality Models (Hall, 2005). These are divided into three main categories as shown below.

6.1. Preferred/recommended models

Recommended models are refined air dispersion models that are currently listed in the Guideline on Air Quality Models and are required to be used for State Implementation Plan revisions for existing sources and for New Source Review and Prevention of Significant Deterioration programs in the USA. In other words, they are air dispersion models that are well accepted and commonly used in many countries, not only in the USA.

6.2 Alternative Models

Alternative models refer to air dispersion models that are not listed in the Guideline on Air Quality Models, but can be utilized in regulatory applications as alternatives to the preferred/recommended models with case-by-case justification to the Reviewing Authority. Some of them were once accepted as recommended models, but they have already been withdrawn due mainly to availability of superior model i.e. AERMOD modeling system (see appendix E for details on the U.S. EPA's alternative models).

6.3 Screening models

Screening models are referred to models that are regularly used before applying refined/recommended models to determine whether refined modeling is required or not. Its data input requirement and complexity and much less than that of refined models.

7. Model Selection

As there is presently a variety of air dispersion models available for users and the extent to which each of these dispersion models is appropriate to the evaluation of a certain source impact differs, the selection of air dispersion model suitable for the characteristics of a source of interest becomes one of the key elements of an effective air dispersion modeling study. When choosing the most appropriate model, the key factors to consider include downwash issue, availability of resources, land-sea interface, detail and accuracy of the data base, level of detail and accuracy required for an analysis, technical competence of model users, and meteorological and topographical complexities of the area (British Columbia Ministry of Environment, 2006).

In doing this research study, model selection was done by choosing the most appropriate air dispersion model from regulatory or preferred/recommended models approved by the U.S. EPA. These models are listed below.

7.1 AERMOD modeling system

Introduced by the American Meteorological Society/Environmental Protection Agency Regulatory Model Improvement Committee (AERMIC), AERMOD is a steady-state dispersion model, designed for use in both simple and complex terrain, that simulates essential atmospheric physical processes and provides concentration estimates over a wide range of meteorological conditions and modeling scenarios based upon Gaussian plume concept. It includes two data preprocessors for streamlining data input. These are AERMET and AERMAP.

7.1.1 AERMET

It is a preprocessor for organizing available meteorological data into a format suitable for use, and then calculating atmosphere parameters needed by AERMOD, such as atmospheric turbulence characteristics, mixing heights and friction velocity.

7.1.2 AERMAP

It is a preprocessor for simplifying and standardizing terrain data input for AERMOD to generate location and height data for each receptor location, and to simulate the effects of air flowing over hills and around hills (Hall, 2005).

7.2 CALPUFF modeling system

Originally developed by the Sigma Research Corporation (SRC) in the late 1980’s under contract with the California Air Resources Board (CARB), CALPUFF, designed for use on scales of tens to hundreds of kilometers, is a Gaussian puff dispersion model/non-steady-state model that simulates the effects of time- and space-varying meteorological conditions on pollution transport and transformation. It includes algorithms for near-field effects (e.g. building downwash, coastal interactions effects, and terrain impingement) as well as longer range effects e.g. pollutant removal due to dry deposition and chemical transformation (Hall, 2005). It consists of three main components as shown below.

7.2.1 CALPUFF

It is an air quality dispersion model itself with the main function of calculating output

7.2.2 CALMET

It is a diagnostic three-dimensional meteorological geographical model for simplifying, analyzing and using meteorological & geophysical data input to develop three–dimensional meteorological & geographical fields to be used by CALPUFF. Data input includes upper air sounding, precipitation, land use and land elevation, coastal information, etc.

7.2.3 CALPOST

It is a post-processing package for displaying output after it is calculated by CALPUFF

7.3 BLP

The Buoyant Line and Point Source Mode (BLP) is a Gaussian plume dispersion model specifically designed to estimate the concentration of pollutants emitted from aluminum reduction plants. This model can also account for building downwash effects, buoyancy associated with line-source plume rise, plume rise enhancement. The model requires hourly meteorological data input, and will produce time- and space-varying concentrations for a receptor location (Hall, 2005).

7.4 CALINE3

CALINE3 is an air dispersion computer program developed by the California Department of Transportation and the US Federal Highways' Agency (FHA). This model is designed to predict the downwind concentrations of non-reactive pollutants or emissions from traffic based on Gaussian plume dispersion concept. It can model junctions, street canyons, parking lots, bridges, highways and underpasses (Hall, 2005). Given source strength, meteorology, site geometry, and site characteristics, the model can reliably predict contaminant concentrations for receptors located within 150 m of the roadway, although distances up to 500 m are acceptable. The model has adjustments for averaging time and surface roughness, and can handle up to 20 links and 20 receptors (British Columbia Ministry of Environment, 2006).

7.5 CAL3QHC/CAL3QHCR

CAL3QHC/CAL3QHCR is an enhanced version of CALINE3, with the additional traffic algorithm to predict vehicular queue lengths at intersections with traffic stop lights. This model is able to estimate the 1 hour mean air contaminant concentrations, for up to 120 road links and 120 receptors, near traffic signals or complex intersections from both moving and idling vehicles. It uses all the data inputs required for CALINE-3 including: roadway geometries, receptor locations, meteorological conditions, and vehicular emission rates, but it gives more reliable output that CALINE3 does (Hall, 2005).

7.6 OCD

Offshore and Coastal Dispersion (OCD) model is developed to simulate the effect of offshore non-reactive pollutants/emissions from point, area or line sources on the air quality of coastal region based on Gaussian plume dispersion concept. OCD is applicable for overwater sources where onshore receptors are below the lowest source height. Where onshore receptors are above the lowest source height, offshore plume transport and dispersion may be modeled on a case-by-case basis in consultation with the appropriate reviewing authority (Hall, 2005). This model requires hourly meteorological data input from both over water and overland. This data input includes wind direction, wind speed, over water air temperature and relative humidity.

7.7 ISC3

Industrial Source Complex version 3 (ISC3) is a steady-state Gaussian plume model used to compute the concentration or deposition values from a wide variety of industrial sources. ISC3 can handle up to 1000 sources and 10,000 receptors, and this multi-source model account for the following effects: dry deposition of particles, downwash, plume rise as a function of downwind distance, separation of point sources and limited terrain adjustment. The model accepts hourly meteorological data and source data input to define conditions for plume rise, transport, diffusion and deposition of air pollutants. The typical data input required for this model includes ambient temperature, wind speed, wind direction, dimension of source, emission rate and relative moisture (Hall, 2005). ISC3 basically includes two sub-models used to assess the concentrations of the pollutants with different averaging periods.

7.7.1 ISCST3 (short term)

It is capable of predicting short term (down to 1 hour mean) concentrations arising from industrial sources of interest.

7.7.2 ISCLT3 (long term)

It is capable of estimating long term (annual mean) concentrations arising from industrial sources of interest (Panich and Panich, 2001).

From the regulatory air dispersion models listed above, only AERMOD, CALPUFF and ISC3 models can be used for this research study in which a coal-fired power plant is a source of interest. This is because the other models are designed to use for other types or characteristics of sources. For instance, BLP is suitable for aluminum reduction plant, OCD is developed for over water source, and CALINE3 or CAL3QHC/CAL3QHCR is designed to predict emission from traffic. To select the most appropriate one out of the three models for this research, it is necessary to scrutinize advantages and disadvantages of each of these three models, and then use this information as a basis for deciding which one is the most suitable for estimating the concentrations of pollutants released from Hingrude coal-fired power plant. Below is a table illustrating the comparison between the three models.

Table 5 Comparison of AERMOD, CALPUFF and ISC3 models

Characteristics	AERMOD	CALPUFF	ISC3
Type of Model	Steady state model (Gaussian Plume Model)	Nonsteady state model (Lagrangian puff or advanced model)	Steady state model (Gaussian plume model)
So-called Name	Latest USEPA model for microscale	Three dimensional wind field model	Traditional workhorse model
Model Range	Recommended for assessing short range transport of pollutants (within 50 km)	Used in all regulatory applications including the long-range (up to 300 km) transport of pollutants. It can also be used on a case-by-case basis in situations involving complex flow and non-steady-state cases from fence-line impacts to 50 km.	Recommended for assessing either short range or long range transport of pollutants
Components	Consists of one main component: AERMOD, and two preprocessors: AERMAP and AERMET	Consists of three main components: CALPUFF, CALMET and CALPOST	Has only one main component: ISC3. No need for preprocessors and postprocessors.

Table 5 (Continued)

Characteristics	**AERMOD**	**CALPUFF**	**ISC3**
Status of Model	Currently accepted by the U.S. EPA as regulatory model as a replacement for ISC3	Accepted by the U.S. EPA as regulatory model since 2003	Displaced by AERMOD on Nov 9, 2006, and since then, it can be used for regulatory application upon getting approval from the reviewing authority.
Description of Modeling Approach	Assumes pollutant material is transported in a straight line instantly (like a beam of light) to receptors , but provides better characterization of plume dispersion than ISC3 does	Assumes pollutant material is transported as a continuous series of circles that become increasingly larger the further away from the source. The course of the circles changes direction moving up and then down to show how the model tracks the actual course of the plume downwind which has a more realistic presentation of dispersion than plume models	Assumes pollutant material is transported in a straight line instantly (like a beam of light) to receptors.

Table 5 (Continued)

Characteristics	**AERMOD**	**CALPUFF**	**ISC3**
Description of Modeling Approach	Assumes pollutant material is transported in a straight line instantly (like a beam of light) to receptors , but provides better characterization of plume dispersion than ISC3 does	Assumes pollutant material is transported as a continuous series of circles that become increasingly larger the further away from the source. The course of the circles changes direction moving up and then down to show how the model tracks the actual course of the plume downwind which has a more realistic presentation of dispersion than plume models	Assumes pollutant material is transported in a straight line instantly (like a beam of light) to receptors.
Status of Model	Currently accepted by the U.S. EPA as regulatory model as a replacement for ISC3	Accepted by the U.S. EPA as regulatory model since 2003	Was displaced by AERMOD on Nov 9, 2006, and since then, it can be used for regulatory application upon getting approval from the reviewing authority.

Table 5 (Continued)

Characteristics	**AERMOD**	**CALPUFF**	**ISC3**
Complexity of Model	Slightly sophisticated	Very sophisticated due to large number of variables associated with this model	Slightly sophisticated
Input Requirement	Requires more input data than ISC3 does e.g. urban population for urban option and some surface characteristics (Bowen ratio and surface roughness)	Requires a lot more input data than for a plume model e.g. upper air sounding data, over water data and precipitation data	Used with a minimum of requirements for input data
Accuracy of Result	AERMOD takes the effects of complex terrain into accounts when predicting the dispersion and concentration of air pollutants of interest. Therefore, its accuracy is an improvement over ISC3's ability to predict measured concentrations.	Tends to give more realistic and reliable result than a steady state model does	Up to 50% error

Table 5 (Continued)

Characteristics	AERMOD	CALPUFF	ISC3
Cost for Use of Model	Less costly	Costly as required more input data. The commercial model is far more expensive than a plume model.	Less costly
Time for Use of Model	Quite time-consuming as data input needs to be arranged in the form that can be read by AERMOD	Very time-consuming due to complexity of the model and abundant amount of data input needed to be prepared for running the model	Quite time-consuming as data input needs to be arranged in the form that can be read by ISC3
Type of Terrain	Can be used for either flat or complex terrain, but the more complex the terrain is, the more erroneous the result of the model is	Can be used for either flat or complex terrain.	Provides substantial overprediction in complex terrain, and so it is recommended for calculating air quality impacts in regions of flat terrain only.

Table 5 (Continued)

Characteristics	**AERMOD**	**CALPUFF**	**ISC3**
Interpreting and Reporting the Model Output	Takes longer time to run the model to give the output than ISC3 does because it uses more variables to calculate the concentrations of the pollutants	Uses more time to process to give the output than the other two models	Takes least time to provide the output amongst three models
Skill Requirement	As simple to use as ISC3 if excludes AERMAP	Very complicated to use	Relatively simple to use
Effect of Wind Speed	Not recommended to use for calm or low wind speed conditions	Can be used for calm conditions	Not recommended to use for calm conditions
Assumption of Meteorological Conditions	Assumes that the atmosphere is uniform across the entire modeling domain, and that transport and dispersion conditions exist unchanged long enough for the material to reach the receptor, which rarely occurs in the atmosphere.	Meteorological conditions are assumed to be not constant during the dispersion from source to receptor, which normally happens in the atmosphere. Therefore, the model has high demands on meteorological data.	Assumes that the atmosphere is uniform across the entire modeling domain, and that transport and dispersion conditions exist unchanged long enough for the material to reach the receptor, which rarely occurs in the atmosphere.

Table 5 (Continued)

Characteristics	**AERMOD**	**CALPUFF**	**ISC3**
Effect of Costal Condition	Not suitable for calculating impacts in costal area	Designed to be suitable for calculating impacts in costal area	Not capable of calculating impacts in costal area
Water Transport	Provides poor prediction of pollutant transport and dispersion over water	Gives better prediction of pollutant transport and dispersion over water	Provides poor prediction of pollutant transport and dispersion over water
Downwash Effect	Included within the model	Included within the model	Not included within the model
Source Type	Multiple point, area, line and volume sources	Multiple point, area, line and volume sources	Multiple point, area, line and volume sources
Additional Program Requirements	AERMOD itself can predict potential air quality impacts on the local environment, but needs other programs to transform the output into the picture; otherwise output is in the forms of text only.	CALPUFF itself can predict potential air quality impact on the local environment, but needs other programs to transform the output into the picture; otherwise output is in the forms of text only.	Needs additional program, e.g. PCRAMMET, to convert meteorological data into the file that can be read by ISC3. Other programs are also required to transform the output into the picture; otherwise output is in the forms of text only.

Table 5 (Continued)

Characteristics	**AERMOD**	**CALPUFF**	**ISC3**
Type of Pollutants	Applicable to primary pollutants or non-reactive pollutants	Allowed for the estimation of both primary and secondary pollutant concentrations	Applicable to primary pollutants or non-reactive pollutants
Current Development Phase	Still undergoing development	Still undergoing development	No more development takes place.
Surface Characteristics	Uses many variations of surface characteristics	Uses many variations of surface characteristics	Choice of rural or urban surfaces only
Characteristics of Meteorological Model	Simple meteorological model	Diagnostic 3-dimensional meteorological model	Simple meteorological model

Source: Mauch (2005); Durham (2006); Heath *et al.* (2006); Howard and Sara (2006)

From the table above, it can be seen that ISC3 model has already been withdrawn from the U.S. EPA's recommended models and its output tends to contain error up to 50%. Therefore, ISC3 model should not be used in this research, and so only AERMOD and CALPUFF models are left for selection.

Albeit it is more complex and time-consuming to use CALPUFF model than AERMOD model, it tends to provide more realistic and reliable output, because it simulates the dispersion of the pollutants based on the assumption that meteorological conditions are not constant, which normally occurs in the atmosphere; and that the pollutant is transported as circles that change their direction when there is a change in metrological conditions, which looks apparently more realistic than Gaussian Plume model like AERMOD (see picture below for the difference between plume and puff models). Furthermore, AERMOD model available needs to be run on MS DOS which requires user with a strong background in MS DOS, whereas CALPUFF model available can be run on MS Windows. More importantly, CALPUFF model is also designed to be suitable for calculating the impacts of the pollutant in coastal area while AERMOD is not recommended for this case, reflecting CALPAFF model's suitability for estimating air quality impacts of Hingrude coal-fired power plant, which is only 3.5 kilometers away from the coast.

Consequently, CALPUFF modeling system is selected for use in this research study. Because of this, its overview, model structure, features & options, and data input requirements, need to be studied in order to gain a clear understanding of this model.

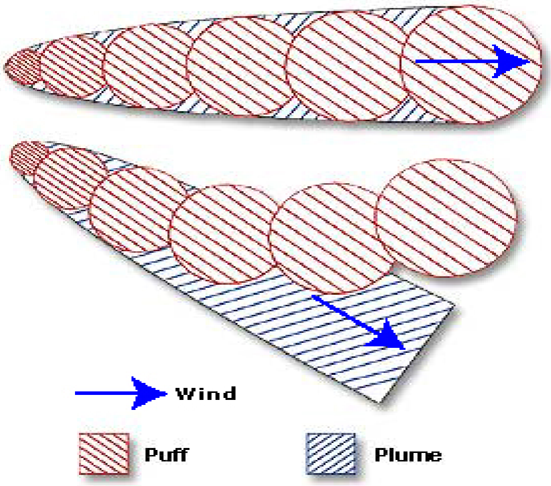


Figure 5 Difference between plume and puff models
Source: Scire *et al.* (2000)

8. CALPUFF Modeling System

8.1 Overview

As explained before, CALPUFF modeling system is a multi-layer, multi-species non-steady-state puff dispersion modeling system that simulates the effects of time- and space-varying meteorological conditions on pollutant transport, transformation, and removal (Hall, 2005). CALPUFF treats a continuous emission point source as a series of puffs. The puffs are represented diagrammatically by interlocking circles that become increasingly larger the further away from the source. The course of the circles changes direction moving up and then down to show how the model tracks the actual course of the plume downwind as can be seen in the picture below. This enables the model to account for a variety of effects such as spatial variability of meteorological conditions, causality effects, dry deposition and dispersion over a variety of spatially varying land surfaces, plume fumigation, low wind-speed dispersion, pollutant transformation and wet removal (Ministry for the Environment of New Zealand, 2004).

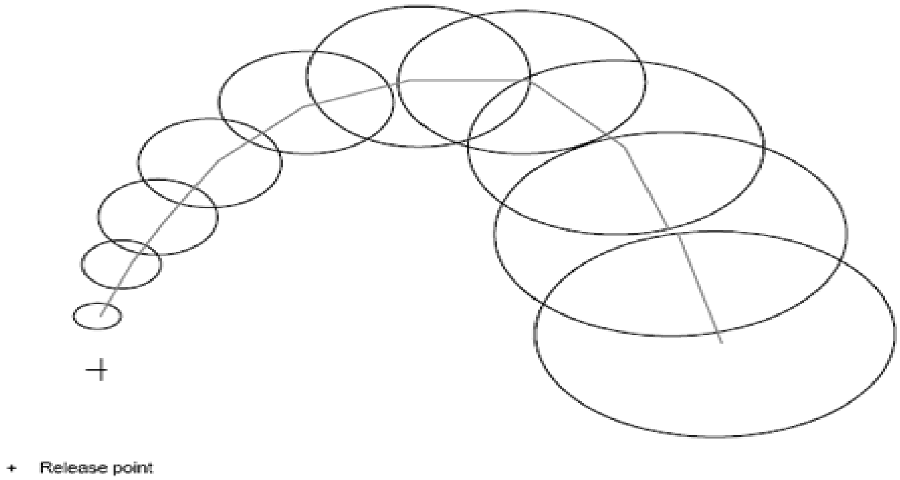


Figure 6 Graphical representation of puff modeling approach

Source: Ministry for the Environment of New Zealand (2004)

The basic equation for the contribution of a puff at a receptor is:

$$C = \frac{Q}{2\pi\sigma_x\sigma_y} g \exp\left[-d_a^2/\left(2\sigma_x^2\right)\right]\exp\left[-d_c^2/\left(2\sigma_y^2\right)\right]$$

$$g = \frac{2}{(2\pi)^{1/2}\sigma_z} \sum_{n=-\infty}^{\infty} \exp\left[-(H_e + 2nh)^2/\left(2\sigma_z^2\right)\right]$$

Where C is the ground-level concentration (g/m^3),

Q is the pollutant mass (g) in the puff,

σ_x is the standard deviation (m) of the Gaussian distribution in the along-wind direction,

σ_y is the standard deviation (m) of the Gaussian distribution in the cross-wind direction,

σ_z is the standard deviation (m) of the Gaussian distribution in the vertical direction,

d_a is the distance (m) from the puff center to the receptor in the along-wind direction,

d_c is the distance (m) from the puff center to the receptor in the cross-wind direction,

g is the vertical term (m) of the Gaussian equation,

H is the effective height (m) above the ground of the puff center, and

h is the mixed-layer height (m).

(Scire *et al.*, 2000)

8.2 Structure of CALPUFF modeling system

CALPUFF generally consists of three main components: CALMET, CALPUFF and CALPOST. For a better understanding of its overall picture, CALPUFF can be however divided into four key components: preprocessing programs, CALMET, CALPUFF and postprocessing programs, as shown below.

8.2.1 Preprocessors

As a door to CALPUFF modeling system, preprocessors include a large set of programs used to arrange, organize, process, transform and compress raw meteorological and geophysical data input required by the model, into the forms and format (file type: DAT) that can be read and utilized by CALMET. As CALPUFF is developed in the USA, preprocessing programs for the raw meteorological data are written to accommodate the file format commonly produced and used by American organizations (e.g. NCDC, CD-144 and FSL format); otherwise user needs to input geophysical and meteorological data into the preprocessors manually by preparing and arranging it in the forms that can be used by these programs. When running these programs, some important setting processes are required to be done properly in order for CALMET to simulate the metrological condition of area of interest with high accuracy, for instance, grid setting for area of interest and setting of meteorological processing period. Preprocessing programs include geophysical, surface meteorological, upper air meteorological, precipitation meteorological and over water meteorological preprocessors, as listed below (Scire *et al*., 2000).

1) Geophysical preprocessor

It is basically a set of preprocessing programs that transform all geophysical data inputted by user, into a data file ready for use by CALMET. These programs are as follows:

1.1) TERREL

It is the program which coordinates the allocation of terrain elevation data from digitized data bases to a user-specified modeling grid. Its output is TERREL.DAT file.

1.2) CTGCOMP

It is a program used to compress USGS land use CTG data file into a very small file. Its output is a CTGCOMP.DAT file.

1.3) CTGPROC

It is a land use preprocessor which reads the compressed CTG land use data file and computes the fractional land use for each grid cell in the user-specified modeling domain. Its output is a LU.DAT file.

1.4) MAKEOGEO

It is the final preprocessor which reads the fractional land use data and terrain data which define land use category mapping, values relating each of the surface parameters to land use and gridded terrain data file, and subsequently generate a GEO.DAT file ready for input to CALMET.

2) Surface meteorological preprocessor (SMERGE)

It is a meteorological program which processes hourly meteorological surface observations from at least three stations in NCDC or CD-144 format and reformats the data into a single file with the data sorted by time rather than station. The output obtained from this program is SURF.DAT file.

3) Upper meteorological preprocessor (READ62)

It is another meteorological program which extracts and processes upper air wind and temperature data from the standard TD-6201 data format or FSL data format, to an output of UP.DAT file.

4) Precipitation preprocessor (PXTRACT and PMERGE)

It is a meteorological program that transforms precipitation data into the single data file ready for use by CALMET. It consists of PXTRACT and PMERGE. PXTRACT program uses raw precipitation data to create precipitation data file which will then be reformatted by PMERGE (PMERGE resolves accumulation periods into hourly values or missing data.) The output file can be formatted or binary (PRECIP.DAT file) which can be directly input into CALMET, containing the precipitation data sorted by hour rather than station.

5) Overwater preprocessor (BUOY)

It is a meteorological program which processes overwater temperature data and air pressure data from overwater observation stations/buoys, and reformat them into the output of SEA.DAT file. BUOY is optional if no overwater available as not many countries have observation buoys in the ocean.

8.2.2 CALMET

CALMET is a meteorological model that uses all geophysical and meteorological data formatted by preprocessors to set and develop the characteristics and condition of hourly wind and temperature fields on a three-dimensional gridded modeling domain. Geophysical and meteorological parameters e.g. temperature, mixing height, running period, wind field grid and wind field model, need to be set here in order to develop the wind field as user wish. The output is in the forms of CALMET.DAT file containing all the information necessary to draw a 3-dimensional temperature and wind field (Scire *et al.*, 2000).

8.2.3 CALPUFF

CALPUFF is an air dispersion model that simulates the transport and dispersion of pollutants emitted from model sources as puffs, by using the temperature and wind field generated by CALMET. Some parameters and effects, such as pollutant species, type of source, receptor location, plume rise effect, land use effect, and terrain effect, need to be set within this program. The primary output files from CALPUFF contain either hourly concentrations or hourly deposition fluxes evaluated at selected receptor locations. The output is in the forms of CONC, DFLX or WFLX.DAT file depending upon what sort of output user needs to obtain from CALPUFF (Scire *et al.*, 2000).

8.2.4 Postprocessors

Postprocessors are referred to programs used to display users-selected portions of the output file from either CALMET or CALPUFF. In other words, they are postprocessing programs with a number of options for the display of the output data file generated by CALMET and CALPUFF. They are basically comprised of PRTMET and CALPOST (Scire *et al.*, 2000).

1) PRTMET

It is the program that reads the binary meteorological data file produced by CALMET, and then reports selected information in numerical formats. Its output basically shows numerical air pressure, turbulence, temperature, wind characteristics within each grid cell and a certain period selected by user. This output is in the forms of PRTMET.LST file, which can be converted into a geographical & meteorological temperature and wind field picture by additional graphical program. Without the use of other graphical programs, the output from PRTMET is just merely numerical values.

2) CALPOST

It is the postprocessing program used to process the output from CALPUFF (concentration, dry deposition or wet deposition), producing tabulations that summarize the results of the simulation, for example, identifying the highest average concentrations at each receptor. Like PRTMET, the output of CALPOST is in the forms of CALPOST.LST file, which can be converted into a picture by additional graphical program illustrating the dispersion and differential concentrations of the pollutants from model sources. Without the use of other graphical programs, the output from CALPOST is just merely numerical values.

The following picture represents the overview of CALPUFF modeling system elements.

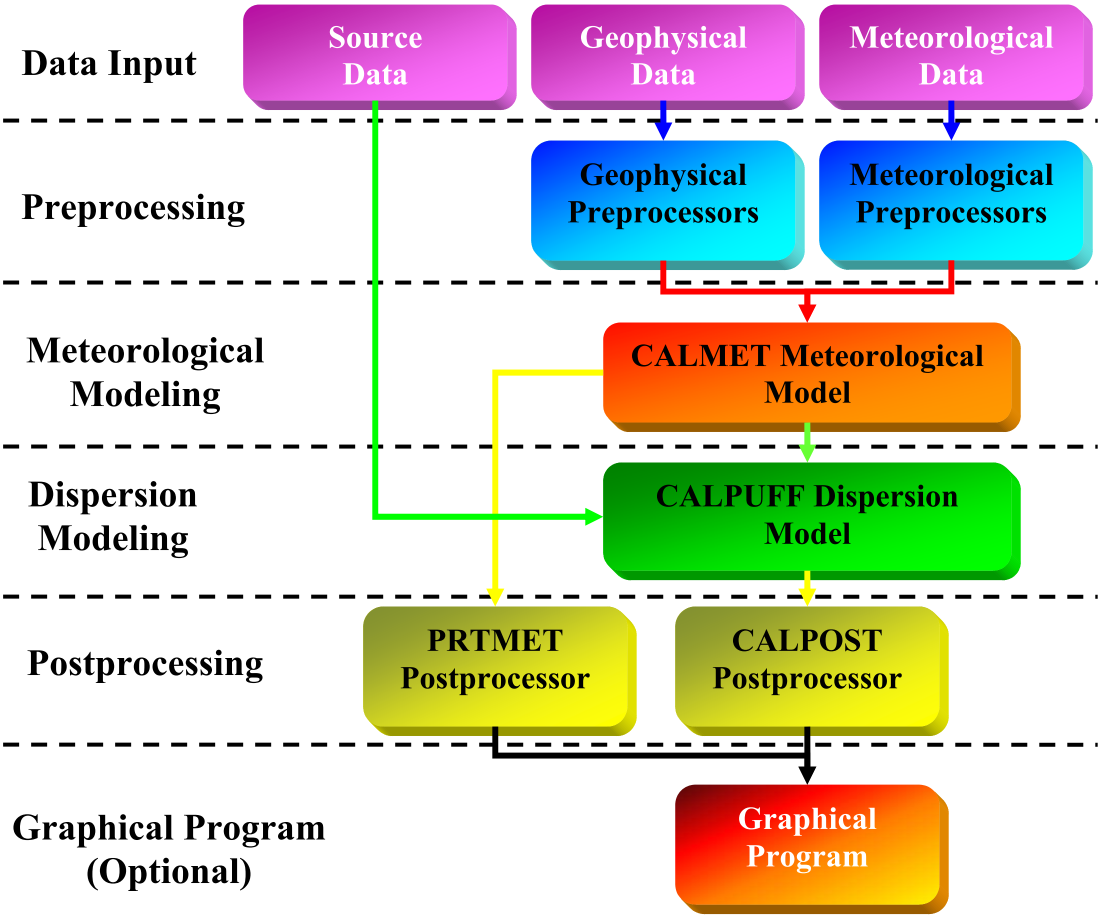


Figure 7 CALPUFF modeling system elements

Source: Scire *et al.* (2000)

8.3 Input data requirement by CALPUFF modeling system

The input data sets required by CALPUFF modeling system roughly include three main categories: geophysical data, meteorological data and source data; each of which covers many parameters and variables. Most of them are essential for the model to run, with the remaining data being optional. For instance, the model can estimate the concentrations of pollutants from model sources, without overwater and precipitation data input if not available. Different data/parameter input is required by each component of CALPUFF modeling system explained above (Scire *et al.*, 2000). All the data input required by CALPUFF modeling system is summarized in the table below.

Table 6 Data input required by CALPUFF modeling system

Data Input Requirements of CALPUFF Modeling System	
Categories of Data Input	**Data Parameters/Variables**
Geophysical Data	• Terrain elevations • Land use categories • Surface roughness lengths • Leaf area indices
Meteorological Data	• Surface air temperature • Surface wind speed • Surface wind direction • Surface air pressure • Surface mixing height • Surface relative humidity • Upper air temperature • Upper wind speed • Upper wind direction • Upper air pressure • Opaque sky cover • Precipitation rate

Table 6 (Continued)

Data Input Requirements of CALPUFF Modeling System	
Categories of Data Input	**Data Parameters/Variables**
Meteorological Data (Continued)	• Precipitation type • Overwater mixing height • Overwater relative humidity • Overwater air temperature • Overwater wind speed • Overwater wind direction • Air-sea surface temperature difference
Source Data	• Type of source • Source location • Source elevations • Pollutant species from sources • Stack diameter • Stack height • Emission rate • Exit velocity • Exit temperature • Receptor location • Number of receptors

Source: Scire *et al.* (2000)

8.4 Major features and options of CALPUFF modeling system

CALPUFF modeling system itself contains many features thus increasing its popularity in many countries worldwide, including Thailand. The major features and options of CALPUFF modeling system are summarized below.

8.4.1. Dry deposition

CALPUFF model contains a full resistance model for the computation of dry deposition rates of gases and particulate matter as a function of geophysical parameters, meteorological conditions and pollutant species. Options are included to allow user-specified, diurnally varying deposition velocities to be used for one or more pollutants instead of the resistance model or to bypass the dry deposition model completely.

8.4.2 Wet deposition

CALPUFF model also contains an empirical scavenging coefficient approach to compute the depletion and wet deposition fluxes due to precipitation scavenging. The scavenging coefficients are specified as a function of the pollutant and precipitation type.

8.4.3 Source types

CALPUFF model are designed to be able to estimate air quality impacts of different kinds of model sources that appear in the real world. These include point sources, line sources, volume sources and area sources.

8.4.4 Graphical user interface

CALPUFF model is equipped with graphical user interface (GUI) to provide point-and-click model set up and data input, thus making the model handy to user, whereas some of the other air dispersion models are still need to be run on MS DOS, which requires user with high skills in MS DOS. Automatic error checking of model inputs is also included with in the model enabling user with less experience or skill to identify error or mistake made when inputting data into the model.

8.4.5 Chemical transformation

CALPUFF model includes options for parameterizing chemical transformation effects. This enables the model to simulate the dispersion of both primary and secondary pollutants/chemicals, and as a result estimate their differential concentrations in the atmosphere.

8.4.6 Overwater and coastal interaction effects

Because CALMET meteorological model contains overwater and overland boundary layer algorithms, the effects of water bodies on the transport, dispersion and deposition of pollutants can be simulated with CALPUFF model. The puff formulation of CALPUFF is designed to handle spatial changes in meteorological and dispersion conditions, including the abrupt changes which occur at the coastline of a major body of water.

8.4.7 Subgrid scale complex terrain

CALPUFF model is equipped with the complex terrain module based on the approach used in the Complex Terrain Dispersion Model (CTDMPLUS). Plume impingement on subgrid hulls is evaluated using dividing streamline to determine which pollutant material is deflected around the sides of a hill and which material is adverted over the hill (Scire *et al*., 2000).

8.5 Current status of CALPUFF modeling system in Thailand

After CALPUFF modeling system was approved by U.S. EPA as a recommended air dispersion model in 2003, CALPUFF modeling system has been adapted and used as a replacement of Gaussian plume dispersion models in many countries e.g. Australia, New Zealand and England. The main reason is that CALPUFF model is capable of simulating the long range dispersion of pollutants in non-steady state condition, which seems to be similar to real atmospheric condition, and as a result it tends to provide more realistic or more accurate output than a Gaussian plume dispersion model does (Ministry for the Environment of New Zealand, 2004).

In Thailand, CALPUFF model was used only amongst a small group of people due mainly to the presence of ISCST and AERMOD dispersion models. However, it started to capture the interest of people in the field of air quality model after it was used instead of AERMOD and ISCST models to conduct air quality impact assessment for Laemchabang industrial estate and Maptaphut industrial estate a few years ago (Surapipith, 2006). Since then, several research studies and tests have been done by government agencies, relevant organizations and consulting companies to determine the accuracy of its output in estimating air quality impacts of industrial sources. Examples of these researches include study on dispersion of SO_2, NO_x and PM_{10} dispersion from Mae Moh power plant, study on air quality impact of industrial plant in Chiang Mai and study on air quality impact of Laemchabang industrial estate in surrounding area. The results of these studies reveal that CALPUFF model can be used to calculate the air quality impacts of industrial sources, and the accuracy of its output is acceptable (Jirungnimitasaku and Kreasuwan, 2004). Hence, its popularity has been rising rapidly in recent years.

Nowadays, government agencies, i.e. Pollution Control Department, and several consulting companies have accepted it as an air dispersion model suitable for estimating the air quality impacts of industrial factories and power plants either located in close proximity to the coastal area or located in complex terrain (e.g. mountains and hills). Other use of CALPUFF model is for predicting long range air quality impacts of the sources e.g. power plants, industrial areas or factories (Surapipith, 2006). Some leading industrial companies, e.g. Siam Cement Group, are now doing the research to ascertain whether CALPUFF model should be used for their factories instead of ISCST3 and AERMOD or not.

As mentioned above, CALPUFF model, like other air dispersion models, requires abundant amount of data input; one of which is emission rate of pollutants of interest. Without it, the model cannot be run to estimate the air quality impacts/concentrations of the pollutants emitted from the plant. As Hingrude coal-fired power plant has not been constructed yet, actual emission rate of the pollutants emitted cannot be measured or obtained. Therefore, emission factors are employed in this research to calculate the potential emission rates of the air pollutants released from the plant.

9. Emission Factors

An emission factor is basically the ratio of the mass of a pollutant emitted to a measured level of source activity. Emission factors are intended to be a representative value trying to relate the quantity of a pollutant released to the atmosphere with an activity associated with release of that pollutant (e.g., pounds of particulate emitted per ton of coal burned and kilograms of particulate emitted per mega-gram of coal burned). Such factors facilitate estimation of emissions from various sources of air pollution. In most cases, these factors are simply averages of all available data of acceptable quality, and are generally assumed to be representative of long-term averages for all facilities in the source category i.e., a population average (North Carolina Department of Environment and Natural Resources, 2007).

The general equation for calculating typical emissions from emission factors is:

$$E = A \times EF$$

Where E is Emissions (such as lb of pollutant/year)
A is Activity or production rate (such as tons coal burned in a year)
EF is Emission factor (such as lb of pollutant / ton coal burned)

A wide variety of the application of emission factors is available. The following illustrates an example of the simplest use of emission factors (calculating carbon monoxide (CO) emissions from distillate oil combustion). Consider an industrial boiler that burns 90,000 liters of distillate oil per day. If the CO emission factor for industrial boilers burning distillate oil is 0.6 kilograms (kg) CO per 1,000 liters of oil burned, then CO emissions is:

= CO emission factor x distillate oil burned/day
= 0.6 x 90
= 54 kg/day

Emissions factors have long been the fundamental tool in developing national, regional, state, and local emissions inventories for air quality management decisions and in developing emissions control strategies. More recently, emissions factors have been applied in determining site-specific applicability and emissions limitations in operating permits by federal, state, local, and tribal agencies, consultants, and industry.

The U.S. EPA has also developed emission factors for a variety of associated activities in the document called Compilation of Air Pollutant Emission Factors or AP-42. Typically, U.S. EPA's emission factors are derived by simply averaging available data of acceptable quality from several tests for a given source category, and assumed to be representative of long-term averages for all facilities in that source category. Owing to its reliability, U.S. EPA's emission factors have been used in the USA as a cost-effective means of estimating emissions of a wide range of facilities or sources over large areas when actual emission cannot be measured or is not available. U.S. EPA's emission factors are also used in some countries which have not had their own emission factors yet or emission factors for some activities are not available (Manning, 1993).

In this research, U.S. EPA's coal combustion emission factors are, because their emission factors for many pollutants emitted from a coal-fired power plant are unavailable, used to calculate potential emission rate of these pollutants to be used as key data input for CALPUFF modeling system to simulate the dispersion of the air pollutants. As the output of CALPUFF modeling system is the differential concentrations of pollutants released from sources, human health risk assessment needs, following the execution of CALPUFF modeling system, to be conducted in order to estimate risks of the pollutants emitted from the coal-fired power plant to local people.

10. Human Health Risk Assessment

Risk Assessment is a scientific process of estimating the likelihood that an undesirable event will occur over a specific time period, and the significance of its consequences, for example, the possibility and consequences of being exposed to air toxic pollutants released from factory, and the probability and impacts of relief valve failure in a factory. Consequently, environmental risk assessment involves an analysis of information on the environment (i.e. air, water and land) integrated with an analysis of information about the effects on human beings and ecological systems (Blazej, 2004). In other words, environmental risk assessment is a combination of human health and ecological risk assessment. As potential impacts and risk of air pollutants from coal combustion on human health are the main interest of this research, human health risk assessment is conducted for this research study.

Human health risk assessment basically combines three types of information: type and severity of negative effects that can be caused by the pollutants, exposure/dose of pollutants expected to cause adverse effects in laboratory animals or human beings, and degree of exposure people are estimate to obtain from the source of pollutants.

From all the above information, the risk of health problems caused by pollutant exposure can be estimated. In doing this, there are four major steps involved as shown below.

10.1 Hazard identification

Hazard identification, also known as the first step in risk assessment, is a process aimed at discovering hazards/toxic substances or pollutants at a certain site/source. There are two main key components to hazard identification: 1) identifying potential hazards, and 2) determining whether or not a particular hazard is likely to cause public health concern and/or environmental deterioration. Both components require a combination of knowledge, experience and judgment because not only a broad spectrum of adverse effects of hazards/pollutants needs to be examined, but also site/process investigation is required. At this point, all the pollutants identified are, by investigating their carcinogenicity, categorized into two main groups: carcinogenic pollutants and non-carcinogenic pollutants (Blazej, 2004).

As for risk assessment within this research, hazard identification were done by collecting and investigating previous studies to identify all the pollutants released from a typical coal-fired power plant. Environmental and human health impacts of these air pollutants were scrutinized and analyzed to determine which one is more or less toxic, and subsequently separate them into two categories: carcinogen and non-carcinogen.

10.2 Exposure assessment

Exposure is principally defined by the concentration of pollutants to which the individual is exposed; time spent in various micro environments, exposure duration, and an individual’s activity pattern which may influence such things as inhalation rate and working hours. Therefore, exposure assessment mainly involves in a process of identifying potential exposure pathways of pollutants to populations and quantifying magnitude, duration and frequency of each exposure pathway. This can be implemented by conducting monitoring or using a model to observe source/emission characteristics (i.e. emission estimate and chemical properties), pollutant dispersion, transport and environmental fate (depending upon climate and geology), exposure pathways (i.e. air and dermal intakes) and potentially exposed population characteristics (i.e. working hours, average ages of workers and duration of exposure). The result of exposure assessment is in the forms of chemical-specific intakes (chemical available for absorption at an exchange boundary) for exposed populations and exposure pathways, and it will be used in conjunction with the result of dose-response assessment, next step in risk assessment process, to estimate human-health risks (Louvar and Louvar, 1998).

There are many chemical-specific intakes needed to be determined in exposure assessment depending upon which exposure pathway of pollutants is available/ identified, such as air intakes, dermal intakes, food intakes, water intakes and so on. In this research, three exposure pathways of pollutants released from Hingrude coal-fired power plant are discovered. These three pathways include air intakes (inhalation), dermal intakes (through skin) and food intakes (via contaminated food consumption) as shown below.

10.2.1 Air intakes

Individual may be exposed to chemicals of potential concern via inhalation vapor-phase chemicals or inhalation of particulates. Air exposure can be computed using the following equation.

$$I_A = \frac{C_A R_I t_E f_E D_t}{W_B t_{avg}}$$

Where I_A is for inhalation intake (mg/kg-day)

C_A is the chemical concentration (mg/m^3)

R_I is the inhalation rate (m^3/hr)

: 30m^3/day, adult, upper bound value

: 20m^3/day, adult, average

t_E is dependent on duration of exposure (hr/day)

: 12 min showering, 90th percentile

: 7 min showering, 50th percentile

f_E is the exposure frequency (day/year)

: Pathway specific and dependent on activities (e.g. showering)

D_t is the exposure duration (year)

: 70 years, conventionally accepted life time

: 30 years, upper 90th percentile time at one residence

: 9 years, 50th percentile median time at one residence

W_B is the body weight (kg)

: 70 kg, average adult weight

t_{avg} is the average time period of exposure (day)

: Pathway-specific for non-carcinogens (i.e. D_t x 365 day/year)

: 70 years for carcinogen (70 years x 365 day/year)

10.2.2 Dermal absorption/intakes

Dermal exposure can be computed using the following equation.

$$I_D = \frac{C_D K_M A_S R_A ABS f_E D_t}{W_B t_{avg}}$$

Where I_D is the dermal absorption (mg/kg-day)

C_D is the chemical concentration in soil (mg/m^3)

K_M is a conversion factor (10^{-6} kg/mg)

A_S is the skin surface area available for contact (cm^2/event)

: 8620 cm^2, 50th percentile area male

R_A is the soil-to-skin adherence factor (mg/cm^2)

: 1.45 mg/cm^2 for commercial potting soil

: 2.77 mg/cm^2 for kaolin clay

ABS is the absorption factor (unitless)

: $1x10^{-3}$ for arsenic, beryllium, and lead

: $1x10^{-1}$ for chlorobenzene, napththalene, and trichlorophenol

f_E is the exposure frequency (events/year)

: 3 times/week in the fall for children

: 5 times/week in the summer when children are not attending school

D_t is the exposure duration (year)

: 70 years, conventionally accepted life time

: 30 years, upper 90th percentile time at one residence

: 9 years, 50th percentile median time at one residence

W_B is the body weight (kg)

: 70 kg, average adult weight

t_{avg} is the average time period of exposure (day)

: Pathway-specific for non-carcinogens (i.e. Dt x 365 day/year)

: 70 years for carcinogen (70 years x 365 day/year)

10.2.3 Food intakes

Individuals may be exposed via contaminated, local food (vegetables, and meat, eggs and dairy products). Ingestion of vegetables can be computed using the following equation.

$$I_V = \frac{C_V R_I f_I f_E D_t}{W_B t_{avg}}$$

Where I_V is the ingestion of vegetables (mg/kg-day)

C_V is the chemical concentration (mg/kg)

R_I is the ingestion rate (kg/meal)

: 0.05 kg/day for root crops

: 0.25 kg/day for vine crops

: 0.01 kg/day for leafy crops

f_I is the fraction ingested from the contaminated source (unitless)

: 0.2 is average

f_E is the exposure frequency (meals/year)

: Pathway specific

D_t is the exposure duration (year)

: 70 years, conventionally accepted life time

: 30 years, upper 90th percentile time at one residence

: 9 years, 50th percentile median time at one residence

W_B is the body weight (kg)

: 70 kg, average adult weight

t_{avg} is the average time period of exposure (day)

: Pathway-specific for non-carcinogens (i.e. Dt x 365 day/year)

: 70 years for carcinogen (70 years x 365 day/year)

Ingestion of meat, eggs and dairy products can be computed using the following equation.

$$I_M = \frac{C_M R_I f_I f_E D_t}{W_B t_{avg}}$$

Where I_M is the ingestion from meat, eggs and dairy products (mg/kg-day)

C_M is the chemical concentration (mg/kg)

R_I is the ingestion rate (kg/meal)

: 0.3 kg/day for milk

: 0.1 kg/day for meat

: 0.28 kg/meal, beef for 95th percentile

: 0.15 kg/meal, eggs for 95th percentile

f_I is the fraction ingested from the contaminated source (unitless)

: 0.44 on average for beef

: 0.4 on average for dairy products

f_E is the exposure frequency (meals/year)

: Pathway specific

D_t is the exposure duration (year)

: 70 years, conventionally accepted life time

: 30 years, upper 90th percentile time at one residence

: 9 years, 50th percentile median time at one residence

W_B is the body weight (kg)

: 70 kg, average adult weight

t_{avg} is the average time period of exposure (day)

: Pathway-specific for non-carcinogens (i.e. Dt x 365 day/year)

: 70 years for carcinogen (70 years x 365 day/year)

However, the results obtained from the model in this study are just merely the concentrations of the pollutants in the atmosphere, not in the soil and water. More importantly, there is currently no approved theory or equation to convert the atmosphere concentration of the pollutants into the concentrations in the soil or water properly and correctly. Because of this, only one exposure pathway (air intake) was included, and thus only chemical-specific intake for inhalation was calculated when conducting exposure assessment in this study.

10.3 Dose-response assessment

As an integral part of risk assessment process, dose-response assessment, sometimes called toxicity assessment, is a process of investigating relationship between magnitude of exposures to pollutants and their adverse effects, thus identifying specific adverse effects as a function of human exposure (Manning, 1993). At this stage, adverse effects are classified into two major groups: carcinogenic effects and non-carcinogenic effects. A relationship parameter was developed to represent the relationships between the significance of these effects and pollutant exposure. As for carcinogenic effects, slope factor (SF), also known as cancer potency factor, is used while reference dose (RfD) is introduced for non-carcinogenic effects. SF was developed by a study on the relationship between dose of cancer-causing pollutant and cancer response whereas RfD originated from research on the relationship between dose of non-carcinogenic pollutant and non-cancer response.

These parameters are vastly varied depending upon chemical/pollutant and exposure pathway. After these parameters (SF and RfD) for each exposure pathway of pollutant is obtained, they will be combined with the results of exposure assessment to estimate the human health risks later (Louvar and Louvar, 1998). In this research, relevant SF and RfD required were obtained from professional websites and previous studies e.g. textbooks, journal and environmental engineering documents.

10.4 Risk characterization

Risk characterization is, the last step in risk assessment process, referred to the integration of the results of exposure assessment and dose-response assessment to estimate potential carcinogenic effects and non-carcinogenic effects on human health over a certain period of exposure for specific exposure pathway (Manning, 1993). In other words, it is where chemical-specific intakes, and SF and RfD for each exposure pathway are combined together to calculate risks of pollutants to human health. In implementing risk characterization, there are three main steps needed to be done, as listed below.

10.4.1 Quantification of pathway risks

This step is primarily to calculate human health risk of pollutants for each exposure pathway identified in exposure assessment. As potential effects of pollutants for each exposure pathway include carcinogenic effects and non-carcinogenic effects, pathway risks to be estimated at this point can be grouped into two categories: carcinogenic risk and non-carcinogenic risk (Manning, 1993).

As for carcinogenic effects, carcinogenic risk is directly related to the intakes. The following equation is used to compute carcinogenic risk for each exposure pathway.

$$\text{Carcinogenic Risk (R)} = \text{CDI} \times \text{SF}$$

Where R is the probability of an individual developing cancer (unitless)

CDI is the chronic daily intake averaged over 70 years (mg/kg-day)

SF is the slope factor (kg-day/mg)

With respect to non-carcinogenic effects, non-carcinogenic risk is assessed by comparing exposure levels or intake of pollutants over a specific period with a corresponding reference dose (RfD) of similar exposure period. This is referred to a non-cancer hazard index (HI). Below is an equation used to compute non-cancer hazard index.

$$HI = I/RfD$$

Where I is the exposure level or chemical-specific intake (mg/kg-day)

RfD is the reference dose (mg/kg-day)

10.4.2 Combination of pathway risks

In order to estimate the total human health risk of pollutants, each pathway risk calculated previously needs to be combined together with the assumption that risk for each exposure pathway can be added up and dose additivity is valid for both carcinogenic effects and non-carcinogenic effects (Manning, 1993). In other words, total risk to human health is derived from the sum up of pathway risks, and the result is in the forms of total carcinogenic risk and total non-carcinogenic risk.

As with carcinogenic effects, total carcinogenic risk for simultaneous exposure can be computed using the following equation.

$$Risk_T = \sum_{i=1}^{n} Risk_i$$

$$Risk_i = Risk\ (pathway\ 1) + Risk\ (pathway\ 2) + \ldots + Risk\ (pathway\ i) \quad or$$

$$Risk_i = CDI_1 \text{ x } SF_1 + CDI_2 \text{ x } SF_2 + \ldots + CDI_i \text{ x } SF_i$$

Where $Risk_T$ is the total pathway cancer/carcinogenic risk expressed as unitless probability

$Risk_i$ is the risk estimate for the ith substance/pollutant
Risk (pathway i) is the risk estimate for ith pathway
n is the number of simultaneous exposures

As for non-carcinogenic effects, total non-cancer risk can be represented as total exposure hazard index (THI) which can be computed in the following equation.

$$THI = \sum_{i=1}^{n} HI_i$$

$$HI_i = HI \text{ (pathway 1)} + HI \text{ (pathway 2)} + \ldots + HI \text{ (pathway i) or}$$

$$HI_i = (I_1/RfD_1) + (I_2/RfD_2) + \ldots + (I_i/RfD_i)$$

Where THI is the total exposure hazard index (total non-cancer risk) for multiple pathways

HI_i (pathway i) is non-cancer hazard index for ith substance
HI (pathway i) is non-cancer hazard index for ith pathway
I_i is chemical-specific intake for ith pathway
RfD_i is reference dose for ith pathway
n is the number of simultaneous exposures

10.4.3 Evaluation of total exposure risks

Following the combination of pathway risks, it is necessary to ascertain whether total exposure cancer risk and non-cancer risk obtained are acceptable or not, so that monitoring systems or risk mitigation measures can be developed and implemented if not acceptable. This can be done by comparing total exposure risks with acceptable risk limits/standards; if total exposure risks exceed these limits, then they are considered unacceptable risk or vice versa (Louvar and Louvar, 1998).

With respect to the acceptable carcinogenic risk level, many countries worldwide have established their own limits ranging from 10^{-6} to 10^{-4} whereas Hazardous Index (HI) not more than one indicates no concern for potential non-carcinogenic effects. In this research, the U.S. EPA's acceptable carcinogenic and non-carcinogenic risk levels for regulation were employed. These U.S. EPA's acceptable risk levels are described below (Kolluru *et al*., 1996).

For carcinogenic risk,

$R > 10^{-6}$	Likely to cause carcinogenic effects
$R \leq 10^{-6}$	Unlikely to cause carcinogenic effects

For non-carcinogenic risk,

$THI > 1$	Likely to cause non-carcinogenic effects
$THI \leq 1$	Unlikely to cause non-carcinogenic effects

Below is a diagram illustrating four main steps in human health risk assessment process.

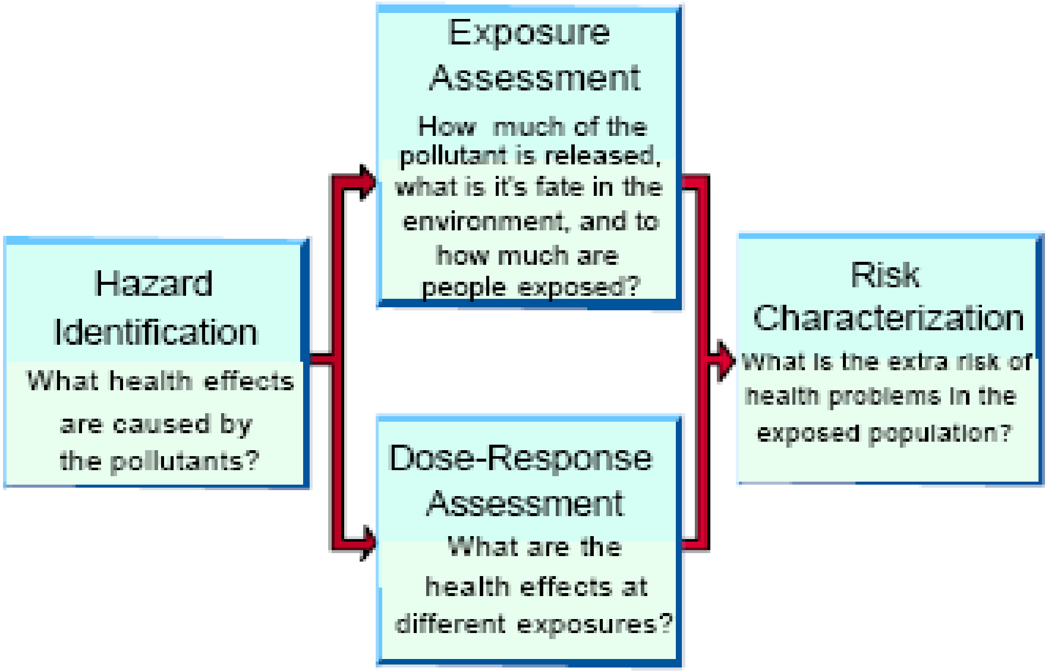


Figure 8 4 steps human health risk assessment process

Source: Manning (1993)

Because risk assessment is an iterative process that will be reviewed as it progresses, there is, after it is completed, a need to review and reassess the site/situation/source periodically as new information becomes available or circumstances change to ensure that risk assessment is still protective.

MATERIALS AND METHODS

Materials

Materials and equipments used for conducting this study are listed below.

1. Personal Computer, Pentium 4, CPU 3.06 GHz, HD 180 GB, RAM 512 MB
2. Personal Laptop, Pentium 4, CPU 2.00 GHz, HD 30 GB, RAM 256 MB
3. Software CALPUFF Modeling System Version Beta 6.0.306
4. Software Surfer Version 8.0
5. Software Google Earth Version 4.1.7087.5048 (Beta)
6. HP Color Laser Jet 2500 L Printer
7. Meteorological data 2006 for the area near the proposed location of Hingrude coal-fired power plant
8. Geophysical data for proposed location of Hingrude coal-fired power plant
9. Source data of proposed Hingrude coal-fired power plant
10. U.S EPA's coal combustion emission factors
11. Slope factors and reference doses for 27 selected air pollutants tested in CALPUFF modeling system
12. Ambient air standards of Thailand

Methods

There are nine consecutive steps in performing this research study. These steps were conducted from 2007 to 2008. Each step was considerably and thoroughly carried out, and consequently findings from each would be used for later step. Details of these steps are presented below.

1. Literature Review

This step was to conduct a primary research for previous studies on three main areas in both Thailand and other countries as shown below.

1.1 Coal combustion

This area includes the following topics: characteristics and operation of coal combustion processes, actual and potential air pollutants released from a typical coal-fired power plant, their characteristics, properties, environmental fate, environmental impacts, health-related effects and hazard ranking system. These topics were thoroughly investigated and studied to discover air pollutants emitted from a typical coal-fired power plant, their environmental impacts and adverse effects on human health and which one of them tend to contribute to more hazard or less hazard.

1.2 Air dispersion models

This area covers several topics: types of air dispersion models approved by the U.S. EPA, their characteristics, main features, advantages and disadvantages, data input requirement, recommended application and key factors to consider for model selection. The purpose of studying these topics is to select the most appropriate air dispersion model for estimating air quality impacts of the air pollutants released from Hingrude coal-fired power plant on near villages.

1.3 Human health risk assessment

Topics in this area include definition of human health risk assessment, its procedure and components, formulae for performing risk assessment, relevant and required variables/parameters and risk standards/ acceptable risk levels. This information helped select proper formulae required to carry out human health risk assessment, and determine the significance of risks assessed.

The studies include several text books, journal documents, conference papers, Thailand governmental environment documents, and educational and environmental engineering professional websites. Consequently, facts and useful research data studied were collected as shown in Literature Review, and these would be used as knowledge foundations for later steps.

2. Data Collection

This step was mainly to collect all relevant information needed to run an air dispersion model selected (CALPUFF modeling system), determine air quality impacts and calculate human health risks of the air pollutants released from Hingrude coal-fired power plant to local people.

All necessary data input for running CALPUFF modeling system include source data (U.S. EPA's coal combustion emission factors for air pollutants emitted from a typical coal-fired power plant, proposed stack diameter, stack height, exit temperature, exit velocity, and location of Hingrude coal-fired power plant), geophysical data (characteristics of terrain, land use and terrain surface elevation) and meteorological data 2006 for the area of Hingrude coal-fired power plant (wind speed, wind direction, air pressure, air temperature, precipitation rate, mixing height, opaque sky cover, relative humidity and air-sea surface temperature difference).

Source data were collected from U.S. EPA website and EIA report for Hingrude coal-fired power plant whilst geophysical data were gathered from the Land Development Department and U.S. Geological Survey website. Required meteorological data for the year 2006 were also collected from eight nearest meteorological observation stations of the Thai Meteorological Department, two nearest meteorological observation stations of the Pollution Control Department and three nearest sea watch buoy of Geo-Informatics and Space Technology Development Agency. The following table represents these 13 meteorological observation stations.

Table 7 Meteorological observation stations used

Data Source	Meteorological Observation Station
Thai Meteorological Department	1. Phetchaburi Station 2. Chumphon Station 3. Bangkok Station 4. Prachuap Khiri Khan Station 5. Hua Hin Station 6. Nhong Phap Station 7. Phuket Station 8. Songkhla Station
Pollution Control Department	1. Phuket Station 2. Surat Thani Station
Geo-Informatics and Space Technology Development Agency	1. Phetchaburi Buoy 2. Hua Hin Buoy 3. Ko Tao Buoy

Additionally, information required for determining air quality impacts of the air pollutants released from Hingrude coal-fired power plant, and estimating their human health related risks, e.g. ambient air standards of Thailand, slope factors & reference doses for the air pollutants, and characteristics of Hingrude coal-fired power plant, was gathered from professional websites, relevant text books, the Pollution Control Department and EIA report for Hingrude coal-fired power plant. Other relevant organizations/ governmental agencies were also contacted for other necessary documents or information. All the information collected at this stage would be subsequently used as a basis for conducting the following steps.

3. Data Analysis

This step was to thoroughly investigate all the information obtained, and subsequently prepare data required for running CALPUFF modeling system. At this point, irrelevant information collected was ruled out whereas an emphasis was placed upon an analysis of necessary information obtained. In particular, the air pollutants identified in air emission from coal combustion (found in 1st step) were carefully and thoroughly scrutinized, and screened to exclude those with insufficient information for running CALPUFF modeling system and calculating human health related risks, for instance, no slope factor & reference dose or no U.S. EPA's emission factor available (Twenty seven screened air pollutants used in this study were listed in Literature Review.).

Furthermore, collected information required for running CALPUFF modeling system, such as meteorological and geophysical data, were analyzed and prepared in the forms of the file ready for use by the model, e.g. DAT file, both manually and using preprocessing programs (geophysical, surface meteorological, upper meteorological, precipitation and overwater preprocessors). Emission rates of these air pollutants were also calculated based upon U.S. EPA's coal combustion emission factors using the equation mentioned earlier. See appendix F for information on U.S. EPA's coal combustion emission factors for 27 selected air pollutants emitted from a typical coal-fired power plant. All the necessary information was subsequently used to run CALPUFF modeling system and estimating human health related risks in the following steps.

4. Execution of CALPUFF Modeling System

Upon the completion of data analysis, all the relevant and prepared data were used as data input to run CALPUFF modeling system to simulate the diffusion of the air pollutants released from Hingrude coal-fired power plant in a period of one year (from 1 January 2006 to 31 December 2006). To be more specific, geophysical and meteorological data in the form of DAT file (prepared in 3rd step) were put in CALMET (Meteorological modeling component of CALPUFF modeling system) to create one year three-dimensional meteorological field for the area of Hingrude coal-fired power plant. Calculated emission rates of the air pollutants and source data were then used as data input for CALPUFF (Dispersion modeling component of CALPUFF modeling system) to simulate the dispersion of the air pollutants emitted from

Hingrude coal-fired power plant from 1 January 2006 to 31 December 2006, based upon the three-dimensional meteorological field created earlier. The procedure for running CALPUFF modeling system is shown in the figure below.

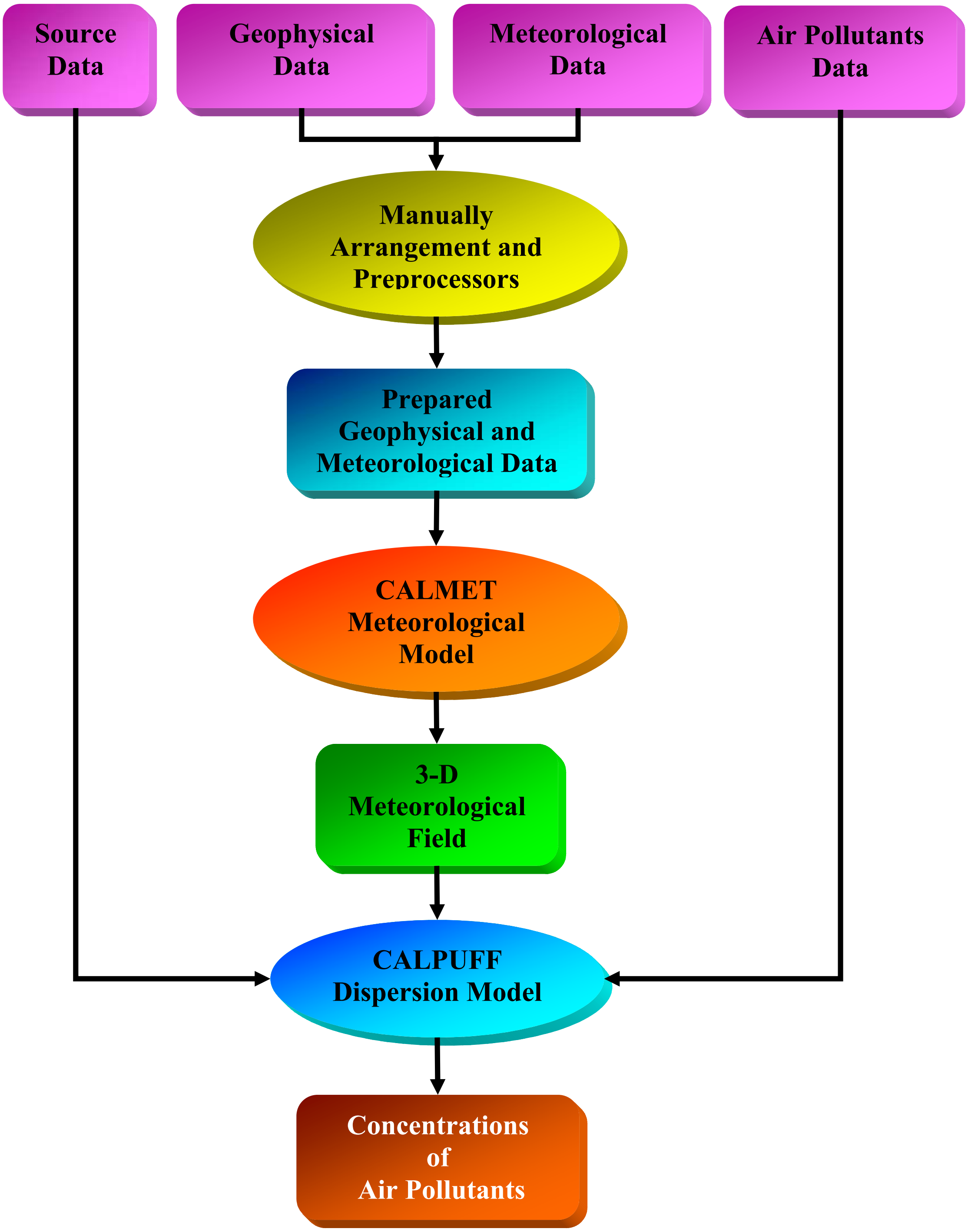


Figure 9 Procedure for running CALPUFF modeling system

At this stage, the model was tested on four villages near Hingrude coal-fired power plant. These villages were Ban Khok Ta Hom, Ban Ang Dhong, Ban Nong Ya Plong and Ban Grude. The proposed locations of Hingrude coal-fired power plant and these four villages are shown in the following figure.

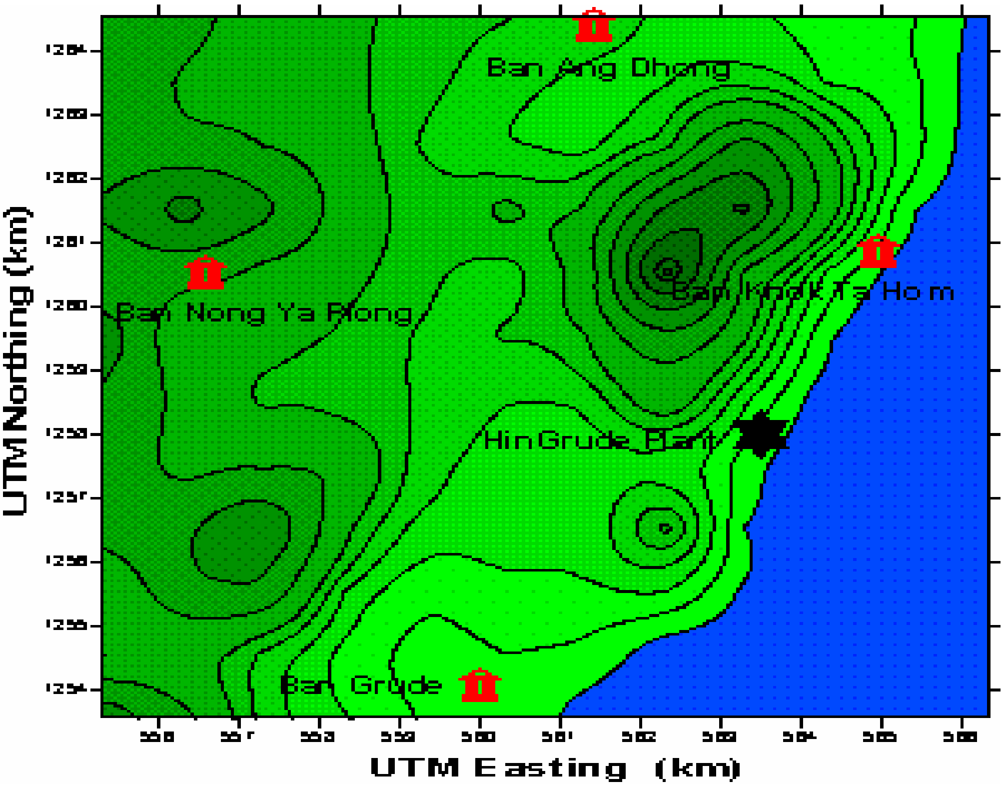


Figure 10 Locations of four villages near Hingrude coal-fired power plant

Below is a table representing coordinates for four villages near Hingrude coal-fired power plant.

Table 8 Coordinates for four villages near Hingrude coal-fired power plant

Coordinates	Latitude	Longitude
Ban Khok Ta Hom	11°24’18.75” N	99°35’43.17” E
Ban Ang Dhong	11°26’15.63” N	99°33’46.51” E
Ban Nong Ya Plong	11°24’08.89” N	99°31’06.56” E
Ban Grude	11°20’38.95” N	99°32’59.51” E

The results received from the model came out as two different types of concentrations: gridded concentrations and discrete concentrations. The first one was referred to hourly concentrations of the air pollutants for an array of gridded receptors in the area of Hingrude coal-fired power plant in 2006. These results would be used for producing graphics of the typical dispersion of the air pollutants in 7th step. The latter represented 1-hour, 8-hour and 24-hour concentrations of the air pollutants in the atmosphere at four villages around Hingrude coal-fired power plant in 2006. These results were on the other hand utilized for determining air quality impacts of the plant on the four villages in 5th step and calculating human health related risks to people residing in these villages in 6th step.

5. Determination of Air Quality Impacts

Once execution of CALPUFF modeling system has been done, the results obtained as the concentrations of the air pollutants in four villages were used in conjunction with ambient air standards of Thailand collected in 2nd step to determine the air quality impacts on four villages near Hingrude coal-fired power plant. This was done by calculating average 1-hour, 8-hour and 24-hour concentrations of air pollutants in four villages, and subsequently comparing them with ambient air standards of Thailand. The villages with the average concentrations higher than the ambient air standards of Thailand were considered to have unacceptable air quality or vice versa. This helped ascertain whether the air pollutants emitted from Hingrude coal-fired power plant caused unacceptable air quality at four villages near the plant or not. The following table illustrates detailed information about the ambient air standards of Thailand.

Table 9 Ambient air standards of Thailand

Ambient Air Standards of Thailand		
Pollutant	**Averaged Time**	**Standards**
Carbon Monoxide	1 hour	34.2 mg/m^3
	8 hour	10.26 mg/m^3
Nitrogen Dioxide	1 hour	0.32 mg/m^3
Ozone	1 hour	0.2 mg/m^3
Sulfur Dioxide	1 hour	780 µg/m^3
	24 hour	0.3 mg/m^3
	1 year	0.1 mg/m^3
Lead	1 month	1.5 µg/m^3
PM10	24 hour	0.12 mg/m^3
	1 year	0.05 mg/m^3
TSP	24 hour	0.33 mg/m^3
	1 year	0.1 mg/m^3

Source: Jirungnimitasaku and Kreasuwan (2004)

6. Estimation of Human Health Risks

The concentrations of the air pollutants obtained from CALPUFF modeling system were also used to estimate carcinogenic and non-carcinogenic risks of these air pollutants to villagers in four villages in order to ascertain whether villagers in these villages were likely to have cancer and/or human health related effects in the advent of Hingrude coal-fired power plant. In doing this, this step was divided into three sub-steps as shown below.

6.1 Exposure assessment

The information collected in 1st step and 2nd step, e.g. proposed number of Hingrude coal-fired power plant workers, distances from the plant to fours villages, location of the villages, number of villagers, work plan schedule for power plant workers and operation duration for the plant, were used to set up, identify or determine routes of exposures, frequency of exposures (f_E), duration of exposures (D_t) and other parameters needed to estimate chemical-specific intakes for each air pollutant at four villages. The results/findings obtained were then used to calculate inhalation chemical-specific intakes for exposed villagers, using the equations mentioned before.

6.2 Dose-response assessment

The information collected in the previous steps, i.e. SF & RfD values for each exposure pathway of the air pollutants discovered, were screened to include only those for the air pollutants tested in CALPUFF modeling system. See appendix G for further information on SFs and RfDs of air pollutants tested in CALPUFF modeling system.

6.3 Risk characterization

Inhalation chemical-Specific intakes for exposed populations obtained from Exposure Assessment were at this stage used in conjunction with concentrations of the air pollutants at four villages obtained from the model in 4th step and SF & RfD values received from Dose-Response Assessment to estimate carcinogenic risks and non-carcinogenic risks of the air pollutants to villagers in four villages near Hingrude coal-fired power plant. The results came out as carcinogenic risks and non-carcinogenic risks for the four villages. Each of the risks calculated was then compared with the risk standard value to identify whether it was acceptable or not. If the risk calculated was higher than the risk standard value, it would be considered unacceptable risk or vice versa.

7. Ranking of Human Health Risks

Once risk calculation has been done, the air pollutants were ranked in order of significance of their carcinogenic risks and non-carcinogenic risks for each of the four villages. This was done to ascertain which air pollutants caused high carcinogenic risks or non-carcinogenic risks to villagers in each of the four villages near Hingrude coal-fired power plant. Hourly typical dispersion graphics of top ranked pollutants for 24 hours were also made to determine the relationship between their dispersions and meteorological factors/conditions. This was done by using Software Surfer Version 8.0 to convert hourly gridded concentrations of these top ranked pollutants obtained in 4th step into hourly graphical dispersions.

8. Research Results

This step was primarily involved in presenting and analyzing all the results/findings obtained from the previous steps. It basically focused on examining the air quality impacts of the air pollutants on four villages received in 5th step, human health related risks to local people calculated in 6th step, and human health risk ranking in 7th step. Some discussions to highlight the strong points of the study results were also provided in this step.

9. Conclusion and Recommendations

This step was conducted mainly to conclude the research study, and to represent research advantages and limitations for better use of the results. This step also presented significant recommendations for further research studies. The following picture shows the procedure of research methodologies for this study.

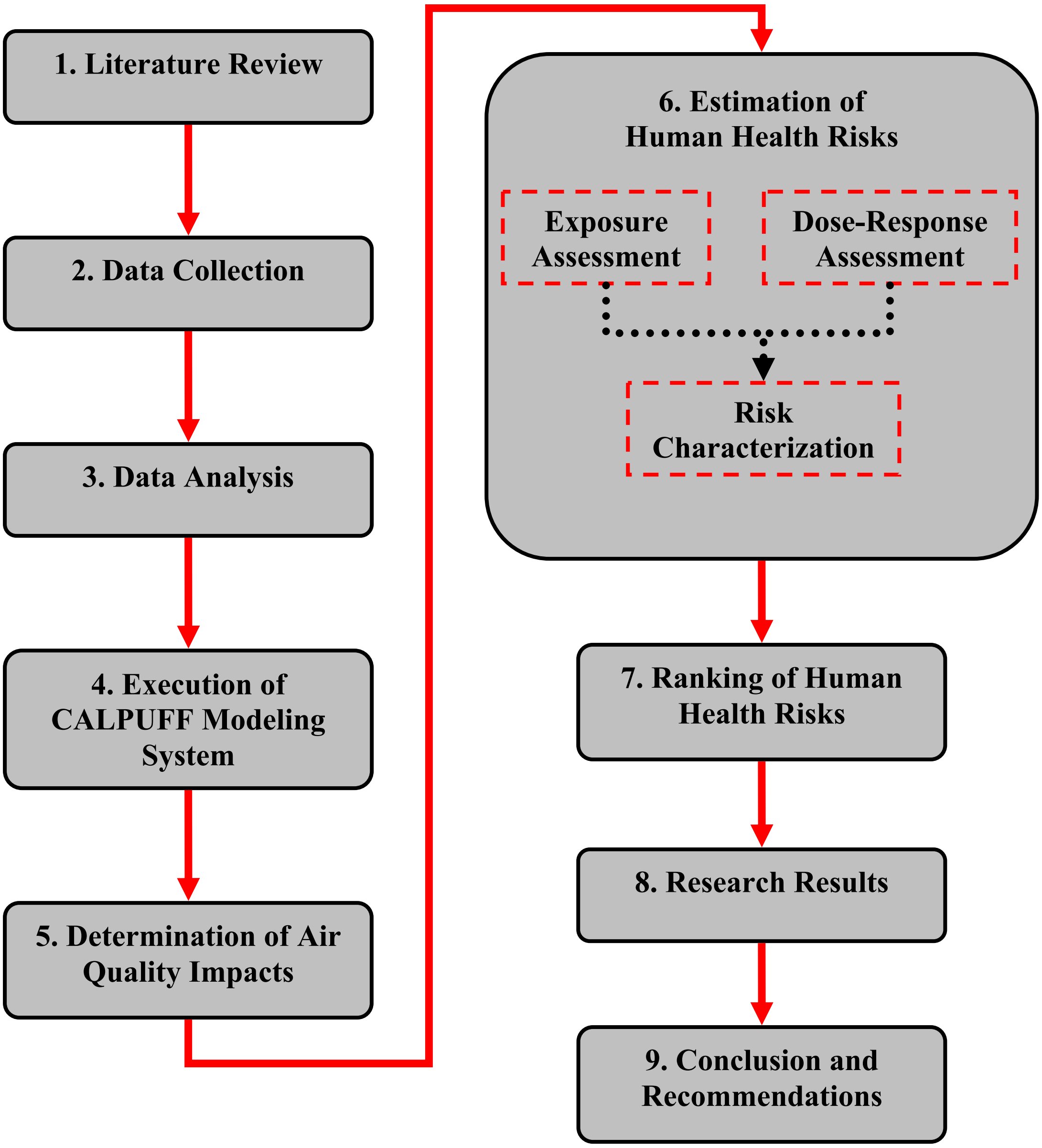


Figure 11 Procedure of research methodologies

RESULTS AND DISCUSSION

Results

Results primarily come from an analysis of the concentrations of 27 air pollutants tested in CALPUFF modeling system for the year 2006.

1. Model Simulation

As explained before, a significant amount of data input is required in order to run CALPUFF modeling system. These data input can be divided into three main categories: meteorological data, geophysical data and source data. The data input used to run the model in this study, together with its sources, is listed in the table below.

Table 10 Data input for simulating CALPUFF modeling system

Type of Data Input	Item	Data Input
Meteorological data	**Surface meteorological data** Surface wind speed, surface wind direction, surface temperature, surface air pressure, mixing height, relative humidity, opaque sky cover and precipitation rate.	These surface meteorological data were collected from five meteorological observation stations of the Thai Meteorological Department and two meteorological observation stations of the Pollution Control Department. These stations are as follows: 1. Phetchaburi Station 2. Chumphon Station 3. Prachuap Khiri Khan Station

Table 10 (Continued)

Type of Data Input	Item	Data Input
Meteorological data		4. Hua Hin Station 5. Nhong Phap Station 6. Phuket Station 7. Surat Thani Station
	Upper air meteorological data Upper wind speed, upper wind direction, upper air temperature and upper air pressure	These upper air data were gathered from three meteorological observation stations of the Thai Meteorological Department. These stations are as follows: 1. Bangkok Station 2. Phuket Station 3. Songkhla Station.
	Overwater meteorological data Overwater wind speed, overwater wind direction, overwater air temperature and overwater pressure	These overwater data were collected from three sea watch buoys of Geo-Informatics and Space Technology Development Agency. 1. Phetchaburi Buoy 2. Hua Hin Buoy 3. Ko Tao Buoy

Table 10 (Continued)

Type of Data Input	Item	Data Input
Geophysical data	Terrain elevations, land use categories, surface roughness lengths and leaf area indices	Terrain elevations and land use categories of the area where proposed Hingrude coal-fired power plant is located, were collected from Land Development Department and U.S. Geological Survey website. Preprocessing programs of CALPUFF modeling system were then used to determine surface roughness lengths and leaf area indices based on these data.
Source data	Type of receptor	1. Gridded receptors 2. Discrete receptors
	Number of receptor	**Four discrete receptors:** 1. Ban Khok Ta Hom 2. Ban Ang Dhong 3. Ban Nong Ya Plong 4. Ban Grude **One gridded receptor:** • 12 km x 12 km, 1 km grid spacing • UTM Nothing from 1253.552 km to 1264.552 km • UTM Easting from 555.302 km to 566.302 km

Table 10 (Continued)

Type of Data Input	Item	Data Input
Source data	Receptor location	**1. Ban Khok Ta Hom** Latitude: 11°24’18.75” N Longitude: 99°35’43.17” E **2. Ban Ang Dhong** Latitude: 11°26’15.63” N Longitude: 99°33’46.51” E **3. Ban Nong Ya Plong** Latitude: 11°24’08.89” N Longitude: 99°31’06.56” E **4. Ban Grude** Latitude: 11°20’38.95” N Longitude: 99°32’59.51” E
	Receptor ground elevation	Ban Khok Ta Hom: 18 m Ban Ang Dhong: 28 m Ban Nong Ya Plong: 40 m Ban Grude: 21 m
	Receptor height above ground	1.7 m for all four villages
	Type of source	Point source
	Source location (Hingrude coal-fired power plant)	UTM Nothing: 1259.575 km, UTM Easting: 561.243 km or Latitude: 11°23’37.47” N, Longitude: 99°33’40.90” E
	Source elevation	29 m above mean sea level
	Type of source releasing	• Continuous emission • Constant emission rate emitted
	Pollutant species tested	27 selected air pollutants listed in Table 3

Table 10 (Continued)

Type of Data Input	Item	Data Input
Source data	Stack diameter	8 m
	Stack height	200 m
	Emission rate	Using emission rates of 27 selected pollutants calculated from U.S. EPA's coal combustion emission factors. These emission rates were calculated and provided in Table 11.
	Exit velocity	18.7 m/s
	Exit temperature	373°K
	Time zone	UTC+0700 Asia/Jakarta
	UTM zone	47
	Hemisphere	Northern hemisphere
	Grid setting	• 12 km x 12 km, 1 km grid spacing • UTM Nothing from 1253.552 km to 1264.552 km • UTM Easting from 555.302 km to 566.302 km
	Datum code	WGS-84
	Running period	1 year; from 1 January 2006 to 31 December 2006

One of the data input requirements for CALPUFF modeling system is emission rates of air pollutants released from coal-fired power plant. Emission rates of 27 selected air pollutant tested in this study were calculated from U.S. EPA's coal combustion emission factors which were gathered from U.S. EPA website (see appendix F for U.S. EPA's coal combustion emission factors). In doing this, U.S. EPA's coal combustion emission factors for each pollutant provided in appendix F was multiplied by unit conversion factor and the daily amount of coal burn at Hingrude coal-fired power plant, as can be seen in the equation below.

$$E = A \times EF$$

An example of emission rate calculation for beryllium is shown below.

U.S. EPA's coal combustion emission factor for beryllium is 0.000021 lb/ton of coal burn (EF = 0.000021 lb/ton). The annual amount of coal burn at Hingrude coal-fired power plant is expected to be around 3.75 million tons, or the daily amount of coal burn at the plant is 10,000 tons approximately (A = 10,000 tons/day). Therefore, the emission rate of beryllium (E) is:

= (0.000021 lb/ton of coal burn) (10,000 tons of coal burn/day)
= 0.21 lb/day
= (0.21 lb/day) / (86,400 second/day)
= 2.4229075×10^{-6} lb/second
= (2.4229075×10^{-6} lb/second) (454 gram/lb)
= 0.0011 gram/second or 0.0011 g/s.

Emission rates for all 27 selected air pollutants listed in Table 3 were calculated based upon their emission factors provided in appendix F, and these emission rates are shown in the table below.

Table 11 Calculated emission rates for 27 selected air pollutants

Pollutant	Emission Factor (lb/ton)	Emission Rate (lb/hr)	Emission Rate (g/s)
Ammonia	0.00171	0.7125057	0.089854886
Antimony	0.000018	0.0075	0.000946
Arsenic	0.00041	0.1708	0.02154
Barium	0.00511	2.1291837	0.268513722
Beryllium	0.000021	0.00875	0.0011
Cadmium	0.000051	0.0213	0.0027
Carbon Monoxide	1.03 (Kton/Mton)	945.3085903	119.2139167
Chromium	0.00026	0.1083	0.0137
Cobalt	0.0001	0.0417	0.00525
Copper	0.00018	0.0750006	0.009458409
2,3,7,8-TCDD	0.000000000393	0.00000016375	0.000000020651
Hydrogen Chloride	1.2	500.004	63.0561
Lead	0.00042	0.175	0.0221
Manganese	0.00049	0.2042	0.0257
Mercury	0.000083	0.0346	0.00436
Nickel	0.00028	0.1167	0.0147
Nitrogen Dioxide	-	-	600
	5.42 (Kton/Mton)	4974.3423	627.3198
Benzo(a)pyrene	0.000000038	0.0000158	0.000001997
Naphthalene	0.000013	0.005417	0.000683
PM$_{10}$	0.45 (Kton/Mton)	413	52.084
Selenium	0.0013	0.5417	0.0683
SO$_2$	-	-	1170
	10.28 (Kton/Mton)	9434.7304	1189.8243
Benzene	0.0013	0.5417	0.0683
CCl$_4$	0.0000609	0.025375203	0.003200095
Chloroform	0.000059	0.0246	0.0031

Table 11 (Continued)

Pollutant	Emission Factor (lb/ton)	Emission Rate (lb/hr)	Emission Rate (g/s)
Vinyl Chloride	0.0000399	0.016625133	0.002096614
Xylene	0.000037	0.0154	0.001944

It is noted that there are two emission rate values for both NO_2 and SO_2 provided in Table 11. The first emission rate values (600 g/s for NO_2 and 1170 g/s for SO_2) were expected emission rates of NO_2 and SO_2 given in EIA report for Hingrude coal-fired power plant whereas the others (627.3198 g/s for NO_2 and 1189.8243 g/s for SO_2) were calculated based upon U.S. EPA's emission factors for coal-fired power plant. As there is only a slight difference between these two emission rate values (27.3198 g/s for NO_2 and 19.8243 g/s for SO_2) and the first values were the one expected to occur according to EIA report for Hingrude coal-fired power plant, the values of 600g/s and 1170 g/s were used as emission rates for NO_2 and SO_2, respectively, in this research whilst emission rates for other pollutants were calculated from U.S. EPA's emission factors coal-fired power plant.

To run the model, geophysical and meteorological data collected were arranged, both manually and using preprocessing programs, in the form of DAT file ready for use by CALPUFF modeling system. All necessary data input (geophysical, meteorological and source data listed in Table 10) were subsequently put into the model to simulate the hourly atmospheric dispersion of 27 selected air pollutants released from Hingrude coal-fired power plant for the year 2006 (from 1 January 2006 to 31 December 2006).

As explained earlier, in this study CALPUFF modeling system was tested on four villages nearest the proposed location of Hingrude coal-fired power plant. These villages include Ban Khok Ta Hom, Ban Ang Dhong, Ban Nong Ya Plong and Ban Grude. The three-dimensional locations of Hingrude coal-fired power plant and the four villages are shown in the figure below.

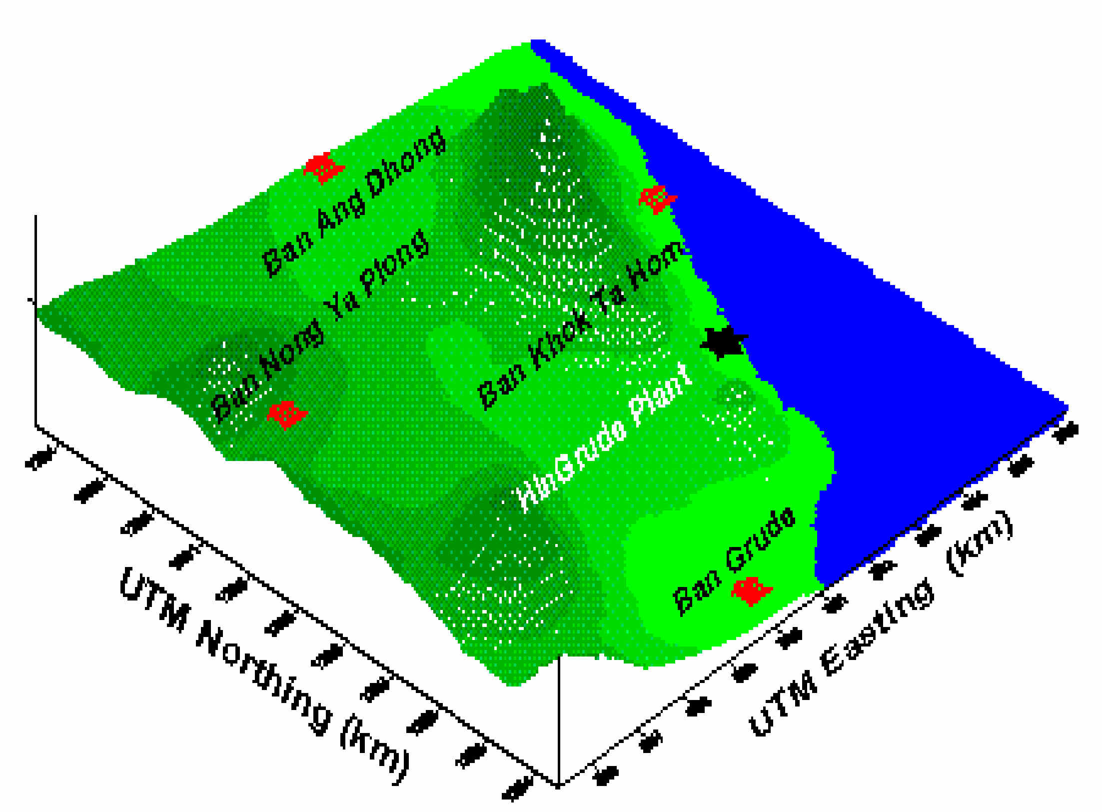


Figure 12 Perspective view of locations of Hingrude coal-fired power plant and four villages

The results of the model came out as 1-hour, 8-hour and 24-hour concentrations of the 27 air pollutants tested at four villages for the year 2006 (from 1 January 2006 to 31 December 2006). These results were used to determine air quality impacts of these air pollutants on four villages near Hingrude coal-fired power plant afterwards.

2. Air Quality Impacts of Hingrude Coal-Fired Power Plant

As explained above, the results from running CALPUFF modeling system include 1-hour, 8-hour and 24-hour concentrations of the 27 air pollutants tested at four villages for the year 2006. To determine the air quality impacts of these 27 pollutants on local people in the area near Hingrude coal-fired power plant, the average 1-hour, 8-hour and 24-hour concentrations at four villages were calculated and then compared with ambient air standards of Thailand. However, only four pollutants out of the 27 pollutants tested in CALPUFF modeling system are included within ambient air standards of Thailand. These four pollutants include sulfur dioxide, nitrogen dioxide, PM_{10} and carbon monoxide (Lead was ruled out because there are only 1-month ambient air standards available for it.).

Consequently, in determining the air quality impacts of Hingrude coal-fired power plant in this study, only the average concentrations of these four air pollutants at four villages were calculated, and subsequently compared with ambient air quality standards of Thailand. The average 1-hour, 8-hour and 24-hour concentrations of these four air pollutants and the ambient air standards for these pollutants are shown in the table below.

Table 12 Average concentrations of SO_2, CO, NO_2 and PM_{10} at four villages

Pollutant		**Average Pollutant Concentrations and Ambient Air Standards of Thailand (mg/m^3)**			
		Ban Khok Ta Hom	**Ban Ang Dhong**	**Ban Nong Ya Plong**	**Ban Grude**
SO_2	1 Hour	1.4366×10^{-1}	1.5191×10^{-1}	1.3769×10^{-1}	6.0139×10^{-2}
	1-Hour Standard	0.78			
	24 Hour	2.7486×10^{-2}	1.8237×10^{-2}	2.4891×10^{-2}	6.0980×10^{-3}
	24-Hour Standard	0.3			
CO	1 Hour	1.4575×10^{-2}	1.5576×10^{-2}	1.4029×10^{-2}	6.2869×10^{-3}
	1-Hour Standard	34.2			
	8 Hour	1.5800×10^{-3}	1.3066×10^{-3}	1.7536×10^{-3}	4.9165×10^{-4}
	8-Hour Standard	10.26			
NO_2	1 Hour	7.3356×10^{-3}	7.8395×10^{-3}	7.1671×10^{-3}	3.1643×10^{-3}
	1-Hour Standard	0.32			
PM_{10}	24 Hour	1.2236×10^{-3}	8.1184×10^{-4}	1.1081×10^{-3}	2.7146×10^{-4}
	24-Hour Standard	0.12			

3. Human Health Risk Estimation

To calculate the carcinogenic and non-carcinogenic risks of 27 air pollutants emitted from the plant to local people in four villages, 24-hour concentrations of the pollutants obtained from running CALPUFF modeling system are required (see appendix I for more information on 24-hour concentrations of 27 pollutants at four villages). In this study, maximum 24-hour concentrations of 27 pollutants were calculated based on the 24-hour concentrations obtained from CALPUFF modeling system, and then used to estimate the carcinogenic and non-carcinogenic risks from the pollutants to people in four villages. This is because human health risks derived from maximum 24-hour concentration represent the critical level or highest possibility for the adverse effects of the pollutants on human health to occur. The maximum 24-hour concentrations of 27 pollutants at four villages are listed in the table below.

Table 13 Maximum 24-hour concentrations of SO_2, CO, NO_2 and PM_{10} at four villages

Pollutant	Maximum 24-Hour Concentration (mg/m^3)			
	Ban Khok Ta Hom	Ban Ang Dhong	Ban Nong Ya Plong	Ban Grude
Ammonia	1.8394 x10^{-5}	6.3453 x10^{-6}	7.2429 x10^{-6}	4.2570 x10^{-6}
Antimony	1.9365 x10^{-7}	6.6804 x10^{-8}	7.6258 x10^{-8}	4.4821 x10^{-8}
Arsenic	4.4094 x10^{-8}	1.5211 x10^{-8}	1.7364 x10^{-8}	1.0206 x10^{-8}
Barium	5.4966 x10^{-5}	1.8962 x10^{-5}	2.1645 x10^{-5}	1.2722 x10^{-5}
Beryllium	2.2518 x10^{-7}	7.7679 x10^{-8}	8.8672 x10^{-8}	5.2117 x10^{-8}
Cadmium	3.2780 x10^{-7}	1.4031 x10^{-7}	1.7765 x10^{-7}	7.8080 x10^{-8}
Carbon Monoxide	2.4403 x10^{-2}	8.4183 x10^{-3}	9.6096 x10^{-3}	5.6481 x10^{-3}
Chromium	2.8045 x10^{-8}	9.6746 x10^{-9}	1.1044 x10^{-8}	6.4910 x10^{-9}
Cobalt	1.0747 x10^{-6}	3.7074 x10^{-7}	4.2321 x10^{-7}	2.4874 x10^{-7}

Table 13 (Continued)

Pollutant	Maximum 24-Hour Concentration (mg/m^3)			
	Ban Khok Ta Hom	**Ban Ang Dhong**	**Ban Nong Ya Plong**	**Ban Grude**
Copper	1.9361 x10^{-6}	6.6790 x10^{-7}	7.6242 x10^{-7}	4.4811 x10^{-7}
2,3,7,8-TCDD	4.2272 x10^{-12}	1.4583 x10^{-12}	1.6646 x10^{-12}	9.7839 x10^{-13}
Hydrogen Chloride	1.2908 x10^{-2}	4.4529 x10^{-3}	5.0830 x10^{-3}	2.9876 x10^{-3}
Lead	4.5240 x10^{-6}	1.5606 x10^{-6}	1.7815 x10^{-6}	1.0471 x10^{-6}
Manganese	5.2610 x10^{-6}	1.8149 x10^{-6}	2.0717 x10^{-6}	1.2177 x10^{-6}
Mercury	8.9252 x10^{-7}	3.0789 x10^{-7}	3.5146 x10^{-7}	2.0657 x10^{-7}
Nickel	3.0092 x10^{-6}	1.0381 x10^{-6}	1.1850 x10^{-6}	6.9648 x10^{-7}
Nitrogen Dioxide	1.2282 x10^{-1}	4.2370 x10^{-2}	4.8367 x10^{-2}	2.8428 x10^{-2}
Benzo(a)pyrene	4.0880 x10^{-10}	1.4102 x10^{-10}	1.6098 x10^{-10}	9.4617 x10^{-11}
Naphthalene	1.3981 x10^{-7}	4.8232 x10^{-8}	5.5057 x10^{-8}	3.2360 x10^{-8}
PM_{10}	1.0662 x10^{-2}	3.6780 x10^{-3}	4.1985 x10^{-3}	2.4677 x10^{-3}
Selenium	1.3981 x10^{-5}	4.8232 x10^{-6}	5.5057 x10^{-6}	3.2360 x10^{-6}
SO_2	2.3951 x10^{-1}	8.2622 x10^{-2}	9.4315 x10^{-2}	5.5434 x10^{-2}
Benzene	1.3981 x10^{-5}	4.8232 x10^{-6}	5.5057 x10^{-6}	3.2360 x10^{-6}
Carbon Tetrachloride	6.5506 x10^{-7}	2.2598 x10^{-7}	2.5796 x10^{-7}	1.5161 x10^{-7}
Chloroform	6.3459 x10^{-7}	2.1891 x10^{-7}	2.4989 x10^{-7}	1.4688 x10^{-7}
Vinyl Chloride	4.2919 x10^{-7}	1.4806 x10^{-7}	1.6901 x10^{-7}	9.9336 x10^{-8}
Xylene	3.9795 x10^{-7}	1.3728 x10^{-7}	1.5671 x10^{-7}	9.2106 x10^{-8}

As mentioned before, inhalation chronic daily intake (CDI) and inhalation average daily intake (ADI) of each pollutant at four villages need to be calculated in order to estimate carcinogenic risks and non-carcinogenic risks, respectively. In calculating CDI and ADI for each of 27 pollutants at four villages, 24-maximum concentrations of the pollutants provided in Table 13 were used in conjunction with other parameters (e.g. exposure duration, exposure frequency, average inhalation rate, etc.) in the following equation.

$$I_A = \frac{C_A R_I t_E f_E D_t}{W_B t_{avg}}$$

An example of the calculation of CDIs for beryllium at four villages is shown below.

Ban Khok Ta Hom

C_A (Beryllium Concentration) = 2.2518 $\times 10^{-7}$ mg/m^3
R_I (Inhalation rate) = 20 m^3/day or 0.833333 m^3/hour (average value for adult)
t_E (Exposure time) = 24 hour/day
f_E (Exposure frequency) = 365 days/year
Dt (Exposure duration) = 25 years (life expectancy of the plant)
W_B (Body weight) = 58.55 kg (average body weight for Thai adult)
T_{avg} (Exposure time period) = 25,550 days (365 days/year x 70 years)

Therefore, CDI for beryllium at Ban Khok Ta Hom is:

$$= \frac{(2.2518 \text{ x}10^{-7} \text{ mg/m}^3)\ (0.833333 \text{ m}^3\text{/hr})\ (24 \text{ hr/d})\ (365 \text{ d/yr})\ (25 \text{ yr})}{(58.55 \text{ kg})\ (25{,}550 \text{ days})}$$

= 2.7471 $\times 10^{-8}$ mg/kg-day.

Ban Ang Dhong

C_A (Beryllium concentration) = 7.7679 $\times 10^{-8}$ mg/m^3
R_I (Inhalation rate) = 20 m^3/day or 0.833333 m^3/hour (average value for adult)

t_E (Exposure time) = 24 hour/day
f_E (Exposure frequency) = 365 days/year
Dt (Exposure duration) = 25 years (life expectancy of the plant)
W_B (Body weight) = 58.55 kg (average body weight for Thai adult)
T_{avg} (Exposure time period) = 25,550 days (365 days/year x 70 years)

Therefore, CDI for beryllium at Ban Ang Dhong is:

$$= \frac{(7.7679 \text{ x}10^{-8} \text{ mg/m}^3)\ (0.833333 \text{ m}^3\text{/hr})\ (24 \text{ hr/d})\ (365 \text{ d/yr})\ (25 \text{ yr})}{(58.55 \text{ kg})\ (25{,}550 \text{ days})}$$

$= 9.4765 \text{ x}10^{-9}$ mg/kg-day.

Ban Nong Ya Plong

C_A (Beryllium concentration) = $8.8672 \text{ x}10^{-8}$ mg/m^3
R_I (Inhalation rate) = 20 m^3/day or 0.833333 m^3/hour (average value for adult)
t_E (Exposure time) = 24 hour/day
f_E (Exposure frequency) = 365 days/year
Dt (Exposure duration) = 25 years (life expectancy of the plant)
W_B (Body weight) = 58.55 kg (average body weight for Thai adult)
T_{avg} (Exposure time period) = 25,550 days (365 days/year x 70 years)

Therefore, CDI for beryllium at Ban Nong Ya Plong is:

$$= \frac{(8.8672 \text{ x}10^{-8} \text{ mg/m}^3)\ (0.833333 \text{ m}^3\text{/hr})\ (24 \text{ hr/d})\ (365 \text{ d/yr})\ (25 \text{ yr})}{(58.55 \text{ kg})\ (25{,}550 \text{ days})}$$

$= 1.0818 \text{ x}10^{-8}$ mg/kg-day.

Ban Grude

C_A (Beryllium concentration) = 5.2117 x10^{-8} mg/m^3
R_I (Inhalation rate) = 20 m^3/day or 0.833333 m^3/hour (average value for adult)
t_E (Exposure time) = 24 hour/day
f_E (Exposure frequency) = 365 days/year
Dt (Exposure duration) = 25 years (life expectancy of the plant)
W_B (Body weight) = 58.55 kg (average body weight for Thai adult)
T_{avg} (Exposure time period) = 25,550 days (365 days/year x 70 years)

Therefore, CDI for beryllium at Ban Grude is:

$$= \frac{(5.2117 \times 10^{-8}\ \text{mg/m}^3)\ (0.833333\ \text{m}^3\text{/hr})\ (24\ \text{hr/d})\ (365\ \text{d/yr})\ (25\ \text{yr})}{(58.55\ \text{kg})\ (25{,}550\ \text{days})}$$

= 6.3581 x10^{-9} mg/kg-day.

CDIs for 27 pollutants at four villages were all calculated based upon their maximum 24-hour concentrations provided in Table 13 and these calculated CDIs are listed in the table below.

Table 14 CDIs for 27 pollutants at four villages

Pollutant	**Inhalation Chronic Daily Intake (mg/kg-day)**			
	Ban Khok Ta Hom	**Ban Ang Dhong**	**Ban Nong Ya Plong**	**Ban Grude**
Ammonia	2.2440E-06	7.7410E-07	8.8360E-07	5.1934E-07
Antimony	2.3624E-08	8.1498E-09	9.3032E-09	5.4680E-09
Arsenic	5.3793E-09	1.8557E-09	2.1183E-09	1.2451E-09
Barium	6.7056E-06	2.3133E-06	2.6406E-06	1.5520E-06

Table 14 (Continued)

Pollutant	Inhalation Chronic Daily Intake (mg/kg-day)			
	Ban Khok Ta Hom	Ban Ang Dhong	Ban Nong Ya Plong	Ban Grude
Beryllium	2.7471E-08	9.4765E-09	1.0818E-08	6.3581E-09
Cadmium	3.9990E-08	1.7117E-08	2.1673E-08	9.5254E-09
Carbon Monoxide	2.9771E-03	1.0270E-03	1.1723E-03	6.8904E-04
Chromium	3.4214E-09	1.1803E-09	1.3473E-09	7.9187E-10
Cobalt	1.3111E-07	4.5229E-08	5.1630E-08	3.0345E-08
Copper	2.3620E-07	8.1481E-08	9.3012E-08	5.4668E-08
2,3,7,8-TCDD	5.1570E-13	1.7791E-13	2.0307E-13	1.1936E-13
Hydrogen Chloride	1.5747E-03	5.4324E-04	6.2010E-04	3.6447E-04
Lead	5.5191E-07	1.9039E-07	2.1734E-07	1.2774E-07
Manganese	6.4182E-07	2.2141E-07	2.5274E-07	1.4855E-07
Mercury	1.0888E-07	3.7561E-08	4.2877E-08	2.5201E-08
Nickel	3.6711E-07	1.2664E-07	1.4457E-07	8.4968E-08
NO_2	1.4984E-02	5.1690E-03	5.9006E-03	3.4681E-03
Benzo(a)pyrene	4.9872E-11	1.7204E-11	1.9639E-11	1.1543E-11
Naphthalene	1.7056E-08	5.8841E-09	6.7167E-09	3.9478E-09
PM_{10}	1.3007E-03	4.4870E-04	5.1220E-04	3.0105E-04
Selenium	1.7056E-06	5.8841E-07	6.7167E-07	3.9478E-07
SO_2	2.9219E-02	1.0080E-02	1.1506E-02	6.7627E-03
Benzene	1.7056E-06	5.8841E-07	6.7167E-07	3.9478E-07
Carbon Tetrachloride	7.9915E-08	2.7569E-08	3.1470E-08	1.8496E-08
Chloroform	7.7417E-08	2.6706E-08	3.0486E-08	1.7919E-08
Vinyl Chloride	5.2359E-08	1.8063E-08	2.0619E-08	1.2119E-08
Xylene	4.8548E-08	1.6748E-08	1.9118E-08	1.1237E-08

An example of the calculation of ADIs for beryllium at four villages is shown below.

Ban Khok Ta Hom

C_A (Beryllium Concentration) = 2.2518×10^{-7} mg/m^3
R_I (Inhalation rate) = 20 m^3/day or 0.833333 m^3/hour (average value for adult)
t_E (Exposure time) = 24 hour/day
f_E (Exposure frequency) = 365 days/year
Dt (Exposure duration) = 25 years (life expectancy of the plant)
W_B (Body weight) = 58.55 kg (average body weight for Thai adult)
T_{avg} (Exposure time period) = 9,125 days (365 days/year x 25 years)

Therefore, ADI for beryllium at Ban Khok Ta Hom is:

$$= \frac{(2.2518 \times 10^{-7} \text{ mg/m}^3)\ (0.833333 \text{ m}^3\text{/hr})\ (24 \text{ hr/d})\ (365 \text{ d/yr})\ (25 \text{ yr})}{(58.55 \text{ kg})\ (9{,}125 \text{ days})}$$

= 7.6919×10^{-8} mg/kg-day.

Ban Ang Dhong

C_A (Beryllium concentration) = 7.7679×10^{-8} mg/m^3
R_I (Inhalation rate) = 20 m^3/day or 0.833333 m^3/hour (average value for adult)
t_E (Exposure time) = 24 hour/day
f_E (Exposure frequency) = 365 days/year
Dt (Exposure duration) = 25 years (life expectancy of the plant)
W_B (Body weight) = 58.55 kg (average body weight for Thai adult)
T_{avg} (Exposure time period) = 9,125 days (365 days/year x 25 years)

Therefore, ADI for beryllium at Ban Ang Dhong is:

$$= \frac{(7.7679 \times 10^{-8}\ \text{mg/m}^3)\ (0.833333\ \text{m}^3/\text{hr})\ (24\ \text{hr/d})\ (365\ \text{d/yr})\ (25\ \text{yr})}{(58.55\ \text{kg})\ (9{,}125\ \text{days})}$$

= 2.6534 x10^{-8} mg/kg-day.

Ban Nong Ya Plong

C_A (Beryllium concentration) = 8.8672 x10^{-8} mg/m^3
R_I (Inhalation rate) = 20 m^3/day or 0.833333 m^3/hour (average value for adult)
t_E (Exposure time) = 24 hour/day
f_E (Exposure frequency) = 365 days/year
Dt (Exposure duration) = 25 years (life expectancy of the plant)
W_B (Body weight) = 58.55 kg (average body weight for Thai adult)
T_{avg} (Exposure time period) = 9,125 days (365 days/year x 25 years)

Therefore, ADI for beryllium at Ban Nong Ya Plong is:

$$= \frac{(8.8672 \times 10^{-8}\ \text{mg/m}^3)\ (0.833333\ \text{m}^3/\text{hr})\ (24\ \text{hr/d})\ (365\ \text{d/yr})\ (25\ \text{yr})}{(58.55\ \text{kg})\ (9{,}125\ \text{days})}$$

= 3.0289 x10^{-8} mg/kg-day.

Ban Grude

C_A (Beryllium concentration) = 5.2117 x10^{-8} mg/m^3
R_I (Inhalation rate) = 20 m^3/day or 0.833333 m^3/hour (average value for adult)
t_E (Exposure time) = 24 hour/day
f_E (Exposure frequency) = 365 days/year
Dt (Exposure duration) = 25 years (life expectancy of the plant)
W_B (Body weight) = 58.55 kg (average body weight for Thai adult)
T_{avg} (Exposure time period) = 9,125 days (365 days/year x 25 years)

Therefore, ADI for beryllium at Ban Grude is:

$$= \frac{(5.2117 \text{ x}10^{-8} \text{ mg/m}^3)\ (0.833333 \text{ m}^3\text{/hr})\ (24 \text{ hr/d})\ (365 \text{ d/yr})\ (25 \text{ yr})}{(58.55 \text{ kg})\ (9{,}125 \text{ days})}$$

$= 1.7803 \text{ x}10^{-8}$ mg/kg-day.

ADIs for 27 pollutants at four villages were all calculated based upon their maximum 24-hour concentrations provided in Table 13 and these ADIs are provided in the table below.

Table 15 ADIs for 27 pollutants at four villages

Pollutant	**Inhalation Average Daily Intake (mg/kg-day)**			
	Ban Khok Ta Hom	**Ban Ang Dhong**	**Ban Nong Ya Plong**	**Ban Grude**
Ammonia	6.2832E-06	2.1675E-06	2.4741E-06	1.4541E-06
Antimony	6.6149E-08	2.2819E-08	2.6049E-08	1.5310E-08
Arsenic	1.5062E-08	5.1959E-09	5.9313E-09	3.4862E-09
Barium	1.8776E-05	6.4772E-06	7.3937E-06	4.3457E-06
Beryllium	7.6919E-08	2.6534E-08	3.0289E-08	1.7803E-08
Cadmium	1.1197E-07	4.7928E-08	6.0683E-08	2.6671E-08
Carbon Monoxide	8.3358E-03	2.8756E-03	3.2825E-03	1.9293E-03
Chromium	9.5798E-09	3.3047E-09	3.7725E-09	2.2172E-09
Cobalt	3.6710E-07	1.2664E-07	1.4456E-07	8.4967E-08
Copper	6.6135E-07	2.2815E-07	2.6043E-07	1.5307E-07
2,3,7,8-TCDD	1.4440E-12	4.9814E-13	5.6861E-13	3.3421E-13
Hydrogen Chloride	4.4092E-03	1.5211E-03	1.7363E-03	1.0205E-03
Lead	1.5453E-06	5.3308E-07	6.0854E-07	3.5768E-07

Table 15 (Continued)

Pollutant	**Inhalation Average Daily Intake (mg/kg-day)**			
	Ban Khok Ta Hom	**Ban Ang Dhong**	**Ban Nong Ya Plong**	**Ban Grude**
Manganese	1.7971E-06	6.1995E-07	7.0767E-07	4.1595E-07
Mercury	3.0487E-07	1.0517E-07	1.2005E-07	7.0562E-08
Nickel	1.0279E-06	3.5460E-07	4.0478E-07	2.3791E-07
NO_2	4.1954E-02	1.4473E-02	1.6522E-02	9.7107E-03
Benzo(a)pyrene	1.3964E-10	4.8171E-11	5.4989E-11	3.2320E-11
Naphthalene	4.7757E-08	1.6475E-08	1.8807E-08	1.1054E-08
PM_{10}	3.6420E-03	1.2564E-03	1.4342E-03	8.4294E-04
Selenium	4.7757E-06	1.6475E-06	1.8807E-06	1.1054E-06
SO_2	8.1814E-02	2.8223E-02	3.2217E-02	1.8936E-02
Benzene	4.7757E-06	1.6475E-06	1.8807E-06	1.1054E-06
CCl_4	2.2376E-07	7.7192E-08	8.8116E-08	5.1788E-08
Chloroform	2.1677E-07	7.4777E-08	8.5359E-08	5.0172E-08
Vinyl Chloride	1.4661E-07	5.0576E-08	5.7732E-08	3.3932E-08
Xylene	1.3594E-07	4.6893E-08	5.3530E-08	3.1462E-08

Once CDIs and ADIs for 27 pollutants at four villages have been calculated, carcinogenic risks and non-carcinogenic risks of these pollutants to people residing in the four villages can be estimated then. As for carcinogenic risk, it was calculated by multiplying CDIs for each pollutant at four villages by their inhalation slope factors (SFs), as can be seen in the equation below (see appendix G for information on SFs of 27 pollutants tested in the model).

$$\text{Carcinogenic Risk (R)} = \text{CDI} \times \text{SF}$$

The results obtained were in the forms of carcinogenic risk for each pollutant at each village. The total carcinogenic risks of 27 pollutants for each village were then calculated by summing carcinogenic risks of 27 pollutants for each village.

An example of the calculation of carcinogenic risks for beryllium at four villages is provided below.

Ban Khok Ta Hom

CDI for beryllium at Ban Khok Ta Hom = 2.7471×10^{-8} mg/kg-day
Inhalation SF for beryllium = 8.4 per mg/kg-day

Therefore, carcinogenic risk for beryllium at Ban Khok Ta Hom is:

= (2.7471×10^{-8} mg/kg-day) (8.4 per mg/kg-day)
= 2.3076×10^{-7}.

Ban Ang Dhong

CDI for beryllium at Ban Ang Dhong = 9.4765×10^{-9} mg/kg-day
Inhalation SF for beryllium = 8.4 per mg/kg-day

Therefore, carcinogenic risk for beryllium at Ban Ang Dhong is:

= (9.4765×10^{-9} mg/kg-day) (8.4 per mg/kg-day)
= 7.9603×10^{-8}.

Ban Nong Ya Plong

CDI for beryllium at Ban Nong Ya Plong = 1.0818×10^{-8} mg/kg-day
Inhalation SF for beryllium = 8.4 per mg/kg-day

Therefore, carcinogenic risk for beryllium at Ban Nong Ya Plong is:

= (1.0818×10^{-8} mg/kg-day) (8.4 per mg/kg-day)
= 9.0868×10^{-8}.

Ban Grude

CDI for beryllium at Ban Grude	= 6.3581 x10^{-9} mg/kg-day
Inhalation SF for beryllium	= 8.4 per mg/kg-day

Therefore, carcinogenic risk for beryllium at Ban Grude is:

= (6.3581 x10^{-9} mg/kg-day) (8.4 per mg/kg-day)
= 5.3408 x10^{-8}.

Carcinogenic risks for 27 pollutants at four villages were all calculated based upon their CDIs listed in Table 14 and SFs provided in appendix G. The total carcinogenic risks of 27 pollutants to people residing in each village were then calculated. These carcinogenic risks are shown in the table below.

Table 16 Carcinogenic risks of 27 pollutants at four villages

Pollutant	**Carcinogenic Risk (R)**			
	Ban Khok Ta Hom	**Ban Ang Dhong**	**Ban Nong Ya Plong**	**Ban Grude**
Ammonia	-	-	-	-
Antimony	-	-	-	-
Arsenic	8.1227E-08	2.8021E-08	3.1987E-08	1.8801E-08
Barium	-	-	-	-
Beryllium	2.3076E-07	7.9603E-08	9.0868E-08	5.3408E-08
Cadmium	2.5154E-07	1.0767E-07	1.3632E-07	5.9915E-08
Carbon Monoxide	-	-	-	-
Chromium	1.4370E-07	4.9571E-08	5.6588E-08	3.3259E-08
Cobalt	-	-	-	-
Copper	-	-	-	-

Table 16 (Continued)

Pollutant	**Carcinogenic Risk (R)**			
	Ban Khok Ta Hom	**Ban Ang Dhong**	**Ban Nong Ya Plong**	**Ban Grude**
2,3,7,8-TCDD	7.7355E-08	2.6686E-08	3.0461E-08	1.7904E-08
Hydrogen Chloride	-	-	-	-
Lead	2.3180E-08	7.9962E-09	9.1281E-09	5.3652E-09
Manganese	-	-	-	-
Mercury	-	-	-	-
Nickel	3.0837E-07	1.0638E-07	1.2143E-07	7.1373E-08
Nitrogen Dioxide	-	-	-	-
Benzo(a)pyrene	1.5361E-10	5.2988E-11	6.0488E-11	3.5552E-11
Naphthalene	-	-	-	-
PM_{10}	-	-	-	-
Selenium	-	-	-	-
SO_2	-	-	-	-
Benzene	4.9463E-08	1.7064E-08	1.9478E-08	1.1449E-08
Carbon Tetrachloride	4.1875E-09	1.4446E-09	1.6490E-09	9.6918E-10
Chloroform	6.2244E-09	2.1472E-09	2.4510E-09	1.4407E-09
Vinyl Chloride	1.6231E-09	5.5994E-10	6.3917E-10	3.7568E-10
Xylene	-	-	-	-
Total Risk	**1.1778E-06**	**4.2719E-07**	**5.0106E-07**	**2.7429E-07**

With respect to non-carcinogenic effects, non-carcinogenic risk was assessed by comparing ADIs for each pollutant at four villages with their corresponding reference doses (RfDs). This is referred to non-cancer hazard index (HI), as can be seen in the equation below (see appendix G for further information on RfDs for 27 pollutants tested in this study).

$$HI = ADI/RfD$$

The results obtained were in the forms of non-carcinogenic risk (HI) for each pollutant at each village. The total non-carcinogenic risk of 27 pollutants for each village were then calculated by summing non-cancer hazard index of 27 pollutants for each village.

An example of the calculation of non-carcinogenic risks (HIs) for beryllium at four villages is provided below.

Ban Khok Ta Hom

ADI for beryllium at Ban Khok Ta Hom = 7.6919×10^{-8} mg/kg-day
Inhalation RfD for beryllium = 0.00000572 mg/kg-day

Therefore, non-carcinogenic risk for beryllium at Ban Khok Ta Hom is:

= (7.6919×10^{-8} mg/kg-day)/ (0.00000572 mg/kg-day)
= 1.3447×10^{-2}.

Ban Ang Dhong

ADI for beryllium at Ban Ang Dhong = 2.6534×10^{-8} mg/kg-day
Inhalation RfD for beryllium = 0.00000572 mg/kg-day

Therefore, non-carcinogenic risk for beryllium at Ban Ang Dhong is:

= (2.6534×10^{-8} mg/kg-day)/ (0.00000572 mg/kg-day)
= 4.6389×10^{-3}.

Ban Nong Ya Plong

ADI for beryllium at Ban Nong Ya Plong = 3.0289 x10^{-8} mg/kg-day
Inhalation RfD for beryllium = 0.00000572 mg/kg-day

Therefore, non-carcinogenic risk for beryllium at Ban Nong Ya Plong is:

= (3.0289 x10^{-8} mg/kg-day)/ (0.00000572 mg/kg-day)
= 5.2953 x10^{-3}.

Ban Grude

ADI for beryllium at Ban Grude = 1.7803 x10^{-8} mg/kg-day
Inhalation RfD for beryllium = 0.00000572 mg/kg-day

Therefore, non-carcinogenic risk for beryllium at Ban Grude is:

= (1.7803 x10^{-8} mg/kg-day) (0.00000572 mg/kg-day)
= 3.1123 x10^{-3}.

Non-carcinogenic risks for 27 pollutants at four villages were all calculated based upon their ADIs listed in Table 15 and inhalation RfDs provided in appendix G. The total non-carcinogenic risks of 27 pollutants to people residing in each village were then estimated. These non-carcinogenic risks are shown in the table below.

Table 17 Noncarcinogenic risks of 27 pollutants at four villages

Pollutant	Noncarcinogenic Risk (HI)			
	Ban Khok Ta Hom	**Ban Ang Dhong**	**Ban Nong Ya Plong**	**Ban Grude**
Ammonia	2.1969E-04	7.5786E-05	8.6507E-05	5.0844E-05
Antimony	1.6537E-04	5.7049E-05	6.5122E-05	3.8276E-05
Arsenic	1.7555E-03	6.0558E-04	6.9130E-04	4.0632E-04
Barium	1.3130E-01	4.5295E-02	5.1704E-02	3.0389E-02
Beryllium	1.3447E-02	4.6389E-03	5.2953E-03	3.1123E-03
Cadmium	-	-	-	-
Carbon Monoxide	8.5222E-04	2.9399E-04	3.3560E-04	1.9725E-04
Chromium	3.3496E-04	1.1555E-04	1.3191E-04	7.7526E-05
Cobalt	1.0697E-02	3.6900E-03	4.2122E-03	2.4757E-03
Copper	6.6135E-05	2.2815E-05	2.6043E-05	1.5307E-05
2,3,7,8-TCDD	-	-	-	-
HCl	7.7084E-01	2.6592E-01	3.0355E-01	1.7841E-01
Lead	3.6022E-03	1.2426E-03	1.4185E-03	8.3375E-04
Manganese	1.2567E-01	4.3353E-02	4.9487E-02	2.9088E-02
Mercury	3.5533E-03	1.2258E-03	1.3992E-03	8.2240E-04
Nickel	-	-	-	-
Nitrogen Dioxide	7.3346	2.5303	2.8884	1.6977
Benzo(a)pyrene	3.4059E-10	1.1749E-10	1.3412E-10	7.8829E-11
Naphthalene	5.5661E-05	1.9202E-05	2.1919E-05	1.2883E-05
PM_{10}	2.5469	8.7857E-01	1.0029	5.8947E-01
Selenium	4.7757E-03	1.6475E-03	1.8807E-03	1.1054E-03
SO_2	9.5354E-01	3.2894E-01	3.7549E-01	2.2069E-01
Benzene	5.5661E-04	1.9202E-04	2.1919E-04	1.2883E-04

Table 17 (Continued)

Pollutant	**Noncarcinogenic Risk (HI)**			
	Ban Khok Ta Hom	**Ban Ang Dhong**	**Ban Nong Ya Plong**	**Ban Grude**
CCl_4	-	-	-	-
Chloroform	-	-	-	-
Vinyl Chloride	5.1261E-06	1.7684E-06	2.0186E-06	1.1864E-06
Xylene	4.7530E-06	1.6396E-06	1.8717E-06	1.1001E-06
Total Risk	**11.9030**	**4.1062**	**4.6873**	**2.7550**

Once the total carcinogenic and non-carcinogenic risks of 27 pollutants at each village have been estimated, they were subsequently compared with U.S. EPA's risk acceptable levels to ascertain which one is acceptable or unacceptable. The results of the comparison are provided in the tables below.

Table 18 Total carcinogenic risks at four villages and carcinogenic risk standards

Receptor	**Total Carcinogenic Risk**	**Acceptable Risk ($\leq 10^{-6}$)**
Ban Khok Ta Hom	1.1778E-06	Unacceptable
Ban Ang Dhong	4.2719E-07	Acceptable
Ban Nong Ya Plong	5.0106E-07	Acceptable
Ban Grude	2.7429E-07	Acceptable

Table 19 Total noncarcinogenic risks at four villages and noncarcinogenic risk standards

Receptor	**Total Non-carcinogenic Risk**	**Acceptable Risk (≤ 1)**
Ban Khok Ta Hom	11.9030	Unacceptable
Ban Ang Dhong	4.1062	Unacceptable
Ban Nong Ya Plong	4.6873	Unacceptable
Ban Grude	2.7550	Unacceptable

4. Human Health Risk Ranking

Once human health risk assessment has been done to identify which total carcinogenetic or non-carcinogenic risks are unacceptable to people in four villages, these risks were subsequently ranked in order of their risk level to ascertain which air pollutant tends to pose the highest risk to local people and which one is likely to cause the lowest risk to them. This is referred to human health risk ranking.

To conduct human health risk ranking in this study, carcinogenic risks and non-carcinogenic risks of each pollutant shown in Table 16 and Table 17 were ranked in order of their risk levels. The carcinogenic and non-carcinogenic risk ranking of 27 pollutants for four villages near Hingrude coal-fired power plant are listed in the following two tables. Carcinogenic risk ranking is shown in Table 20 and non-carcinogenic risk ranking is provided in Table 21.

Table 20 Carcinogenic risk ranking for four villages

Pollutant	**Carcinogenic Risk Ranking**			
	Ban Khok Ta Hom	**Ban Ang Dhong**	**Ban Nong Ya Plong**	**Ban Grude**
Ammonia	-	-	-	-
Antimony	-	-	-	-
Arsenic	5	5	5	5
Barium	-	-	-	-
Beryllium	3	3	3	3
Cadmium	2	1	1	2
Carbon Monoxide	-	-	-	-

Table 20 (Continued)

Pollutant	Carcinogenic Risk Ranking			
	Ban Khok Ta Hom	**Ban Ang Dhong**	**Ban Nong Ya Plong**	**Ban Grude**
Chromium	4	4	4	4
Cobalt	-	-	-	-
Copper	-	-	-	-
2,3,7,8-TCDD	6	6	6	6
Hydrogen Chloride	-	-	-	-
Lead	8	8	8	8
Manganese	-	-	-	-
Mercury	-	-	-	-
Nickel	1	2	2	1
Nitrogen Dioxide	-	-	-	-
Benzo(a)pyrene	12	12	12	12
Naphthalene	-	-	-	-
PM_{10}	-	-	-	-
Selenium	-	-	-	-
Sulfur Dioxide	-	-	-	-
Benzene	7	7	7	7
Carbon Tetrachloride	10	10	10	10
Chloroform	9	9	9	9
Vinyl Chloride	11	11	11	11
Xylene	-	-	-	-

Table 21 Noncarcinogenic risk ranking for four villages

Pollutant	Noncarcinogenic Risk Ranking			
	Ban Khok Ta Hom	Ban Ang Dhong	Ban Nong Ya Plong	Ban Grude
Ammonia	16	16	16	16
Antimony	17	17	17	17
Arsenic	12	12	12	12
Barium	5	4	5	5
Beryllium	7	7	7	7
Cadmium	-	-	-	-
Carbon Monoxide	13	13	13	13
Chromium	15	15	15	15
Cobalt	8	8	8	8
Copper	18	18	18	18
2,3,7,8-TCDD	-	-	-	-
Hydrogen Chloride	4	3	4	4
Lead	10	10	10	10
Manganese	6	5	6	6
Mercury	11	11	11	11
Nickel	-	-	-	-
Nitrogen Dioxide	1	1	1	1
Benzo(a)pyrene	22	22	22	22
Naphthalene	19	19	19	19
PM_{10}	2	6	2	2
Selenium	9	9	9	9
SO_2	3	2	3	3
Benzene	14	14	14	14

Table 21 (Continued)

Pollutant	Noncarcinogenic Risk Ranking			
	Ban Khok Ta Hom	Ban Ang Dhong	Ban Nong Ya Plong	Ban Grude
Carbon Tetrachloride	-	-	-	-
Chloroform	-	-	-	-
Vinyl Chloride	20	20	20	20
Xylene	21	21	21	21

After carcinogenic and non-carcinogenic risk rankings of 27 pollutants for four villages were done, as can be seen in Table 20 and Table 21, these risk rankings were subsequently used to create a final carcinogenic risk ranking and non-carcinogenic risk ranking for 27 pollutants. In doing this, pollutants that have the same risk ranking for four villages were considered to have the same final risk ranking as those risk rankings for four villages. For example, arsenic that has the fifth carcinogenic risk rankings for four villages was ranked to have the fifth carcinogenic risk ranking in final risk ranking.

As for the pollutant that does not have the same risk ranking for four villages, the final risk ranking was considered case-by-case. For instance, hydrogen chloride poses the forth highest carcinogenic risks to people in three villages, and the third highest carcinogenic risk to people in one village. Hence, hydrogen chloride is considered to have the forth carcinogenic risk ranking in final carcinogenic risk ranking. The results of final carcinogenic and non-carcinogenic risk rankings are shown in Table 22 and Table 23.

Table 22 Final carcinogenic risk ranking

Pollutant	Carcinogenic Risk Ranking
Nickel	1
Cadmium	2
Beryllium	3
Chromium	4
Arsenic	5
2,3,7,8-TCDD	6
Benzene	7
Lead	8
Chloroform	9
Carbon Tetrachloride	10
Vinyl Chloride	11
Benzo(a)pyrene	12

Table 23 Final noncarcinogenic risk ranking

Pollutant	Noncarcinogenic Risk Ranking
Nitrogen Dioxide	1
PM_{10}	2
Sulfur Dioxide	3
Hydrogen Chloride	4
Barium	5
Manganese	6
Beryllium	7
Cobalt	8
Selenium	9
Lead	10
Mercury	11
Arsenic	12

Table 23 (Continued)

Pollutant	Noncarcinogenic Risk Ranking
Carbon Monoxide	13
Benzene	14
Chromium	15
Ammonia	16
Antimony	17
Copper	18
Naphthalene	19
Vinyl Chloride	20
Xylene	21
Benzo(a)pyrene	22

5. Risk Estimation for Top Ranked Air Pollutants

As mentioned above, the total carcinogenic risks of 27 pollutants are considered acceptable to people in four villages near Hingrude coal-fired power plant, but these pollutants are likely to cause non-carcinogenic effects on people in four villages. Because of this, an emphasis was placed upon pollutants ranked top in non-carcinogenic risk ranking to ascertain whether these pollutants are likely to cause adverse effects on people in four villages near the plant or not. Hence, human health risk estimation for the pollutants ranked top in non-carcinogenic risk ranking was therefore conducted in this study. As the air quality impacts of NO_2, PM_{10} and SO_2 are usually conducted within EIA for coal-fired power plant, these pollutants (ranked top three in Table 23) were chosen and tested in this study to find out whether the total non-carcinogenic risks of these pollutants are acceptable to people in four villages near Hingrude coal-fired power plant or not.

In estimating the total non-carcinogenic risks of NO_2, PM_{10} and SO_2 for four villages near the plant, non-carcinogenic risks of each of these pollutants calculated and provided in Table 17 were used. These non-carcinogenic risks are listed in the table below.

Table 24 Noncarcinogenic risks of NO_2, PM_{10} and SO_2 at four villages

Pollutant	**Noncarcinogenic Risk (HI)**			
	Ban Khok Ta Hom	**Ban Ang Dhong**	**Ban Nong Ya Plong**	**Ban Grude**
Nitrogen Dioxide	7.3346	2.5303	2.8884	1.6977
PM_{10}	2.5469	8.7857E-01	1.0029	5.8947E-01
SO_2	9.5354E-01	3.2894E-01	3.7549E-01	2.2069E-01

The non-carcinogenic risks of three pollutants at four villages provided in Table 24 were summed together to determine the total non-carcinogenic risks of these pollutants for each village. These total non-carcinogenic risks were then compared with U.S. EPA's acceptable non-carcinogenic risk level to find out which one is acceptable and which one is not. The results are shown in Table 25.

Table 25 Total noncarcinogenic risks of NO_2, PM_{10} and SO_2 at four villages

Receptor	**Total Non-carcinogenic Risk**	**Acceptable Risk (≤ 1)**
Ban Khok Ta Hom	10.8350	Unacceptable
Ban Ang Dhong	3.7378	Unacceptable
Ban Nong Ya Plong	4.2668	Unacceptable
Ban Grude	2.5079	Unacceptable

According to Table 25, the total non-carcinogenic risks of only three top ranked pollutants (NO_2, PM_{10} and SO_2) is merely a little bit lower than the total non-carcinogenic risks of 27 pollutants for four villages in Table 19 (11.9030 for Ban Khok Ta Hom, 4.1062 for Ban Ang Dhong, 4.6873 for Ban Nong Ya Plong and 2.7550 for Ban Grude). If we subtract the total non-carcinogenic risks of NO_2, PM_{10}

and SO_2 from the total non-carcinogenic risks of 27 pollutants, the remaining total non-carcinogenic risks come from the other 24 pollutants. These are shown in the following table.

Table 26 Comparison of total noncarcinogenic risks at four villages

Receptor	**Total Non-carcinogenic Risk**		
	27 pollutants	**NO_2, PM_{10} and SO_2**	**24 pollutants**
Ban Khok Ta Hom	11.9030	10.8350	1.0680
Ban Ang Dhong	4.1062	3.7378	0.3684
Ban Nong Ya Plong	4.6873	4.2668	0.4205
Ban Grude	2.7550	2.5079	0.2471

6. Dispersion of Top Ranked Air Pollutants

Once the calculation of non-carcinogenic risk for NO_2, PM_{10} and SO_2 has been done, hourly typical dispersion graphics of these three pollutants for 24 hours in three seasons (winter, summer and rainy season) were made in order to determine the relationship between their dispersions and meteorological factors/conditions, by using Software Surfer Version 8.0 to convert hourly gridded concentrations of these top ranked pollutants obtained from running CALPUFF modeling system into hourly graphical dispersions. The following figures represent some important hourly dispersion graphics of NO_2, PM_{10} and SO_2 in three seasons (see appendix J for more dispersion graphics of NO_2, PM_{10} and SO_2).

In the following figures, the dispersion of the pollutants was drawn in different colors, according to their atmospheric concentrations. Three color scales are used in these figures. These colors include blue, yellow and red. Blue color represents the area where the concentrations of the pollutants are much lower than the ambient air standards of Thailand (called safe area). Yellow color illustrates the area where the concentrations of the pollutants are a little bit lower than the ambient air standards of Thailand (called sensitive area). Red color indicates the area where the concentrations of the pollutants are higher than the ambient air standards of Thailand (called dangerous area). As the hourly dispersion graphics were made for NO_2, PM_{10} and SO_2, the 1-hour ambient air standards of Thailand for these three pollutants were used to distinguish dangerous area from safe and sensitive area. However, there are no 1-hour ambient air standards of Thailand available for PM_{10}. As U.S EPA is an agency well known and widely accepted by many countries worldwide as an organization that has set up universal standards for environmental protection, 1-hour ambient air quality standards of U.S EPA for PM_{10} was used in this study to indicate dangerous area in hourly dispersion graphics of PM_{10} instead (see appendix H for information on ambient air quality standards of U.S. EPA).

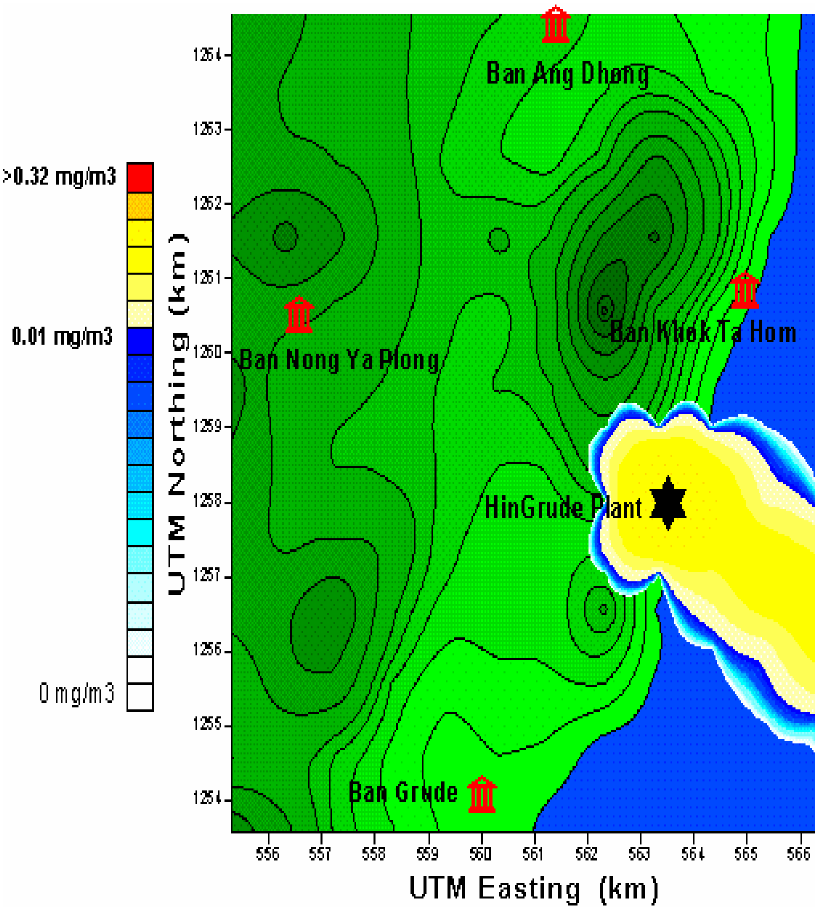


Figure 13 19th hour dispersion of NO_2 in winter

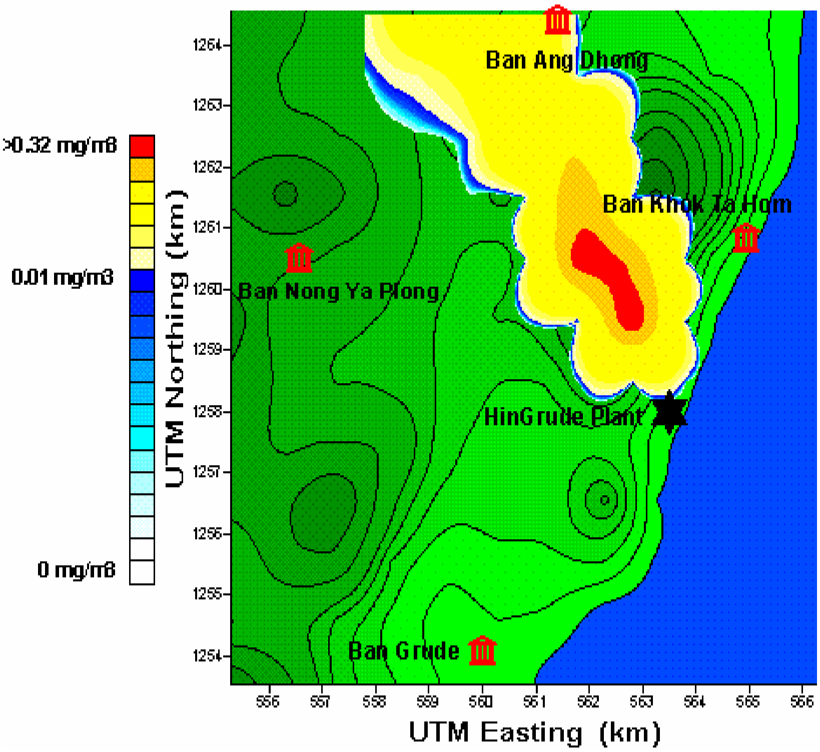


Figure 14 18th hour dispersion of NO_2 in summer

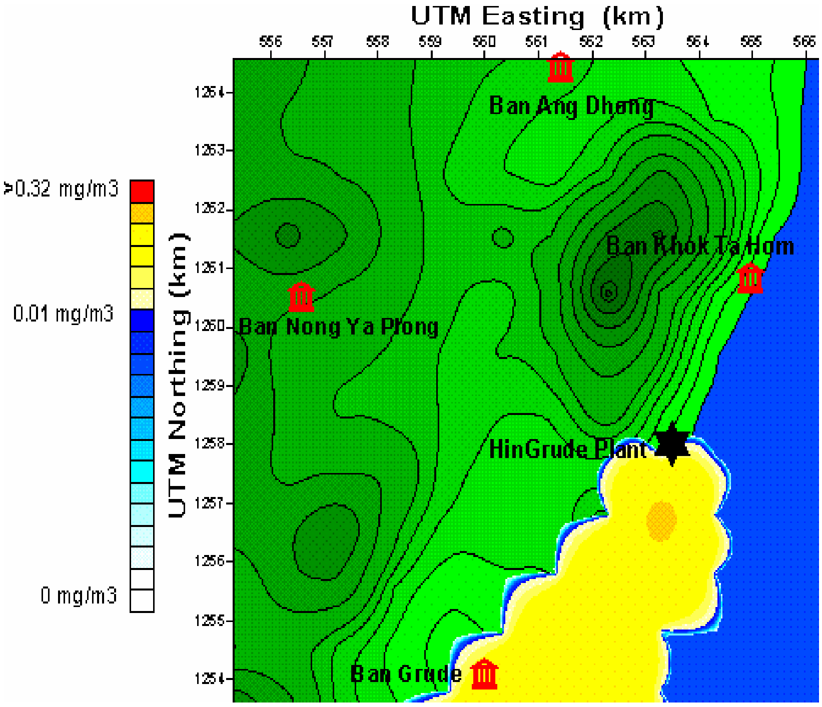


Figure 15 22nd hour dispersion of NO_2 in rainy season

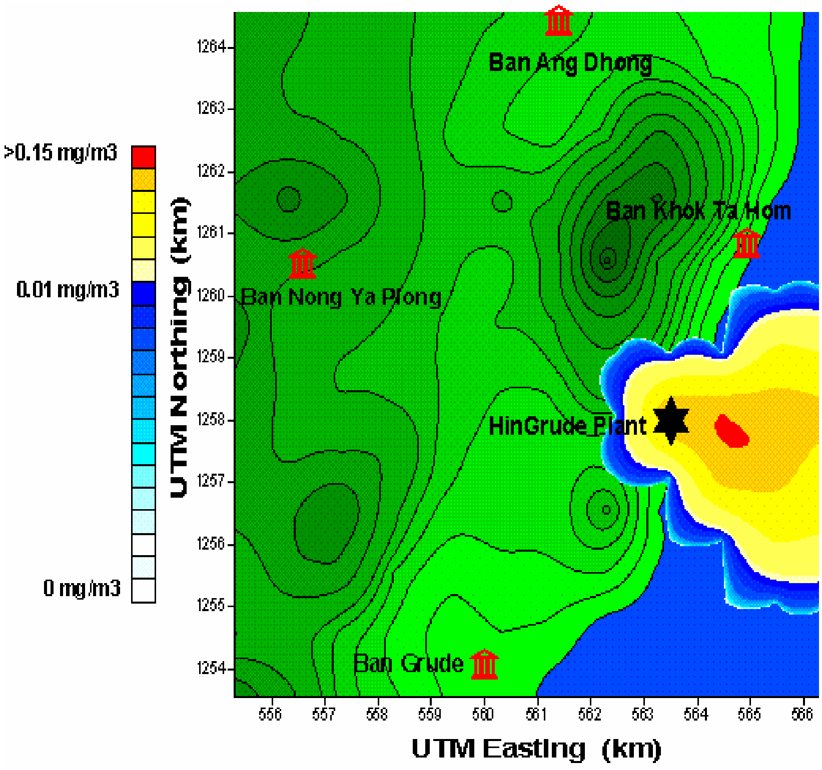


Figure 16 16th hour dispersion of PM_{10} in winter

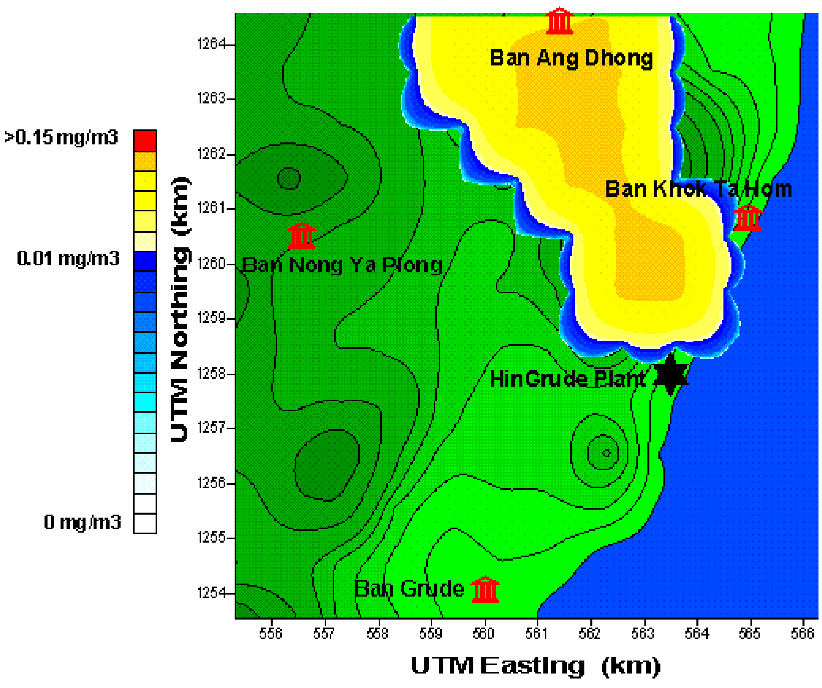


Figure 17 17th hour dispersion of PM_{10} in summer

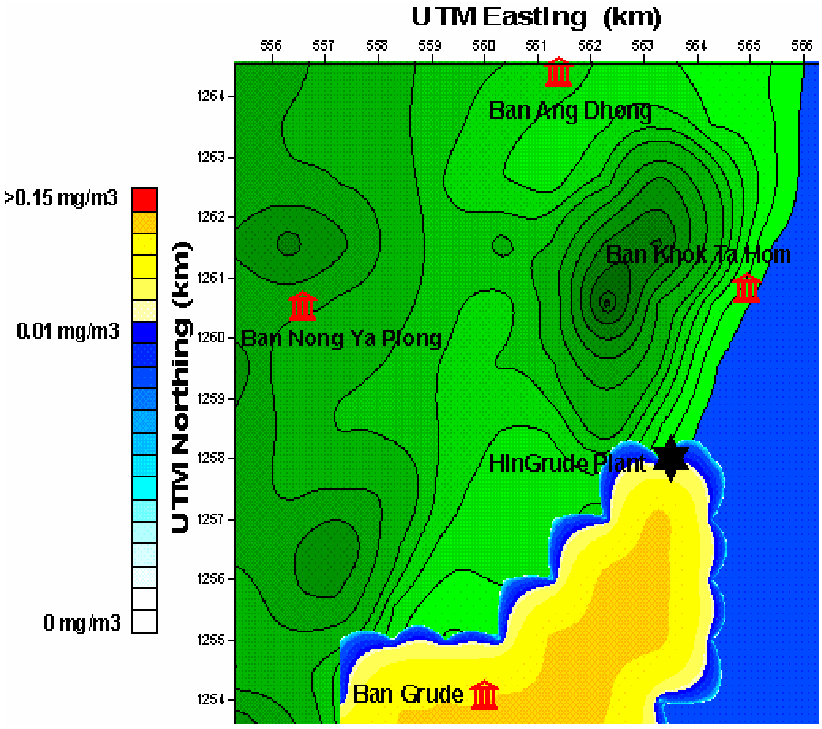


Figure 18 19th hour dispersion of PM_{10} in rainy season

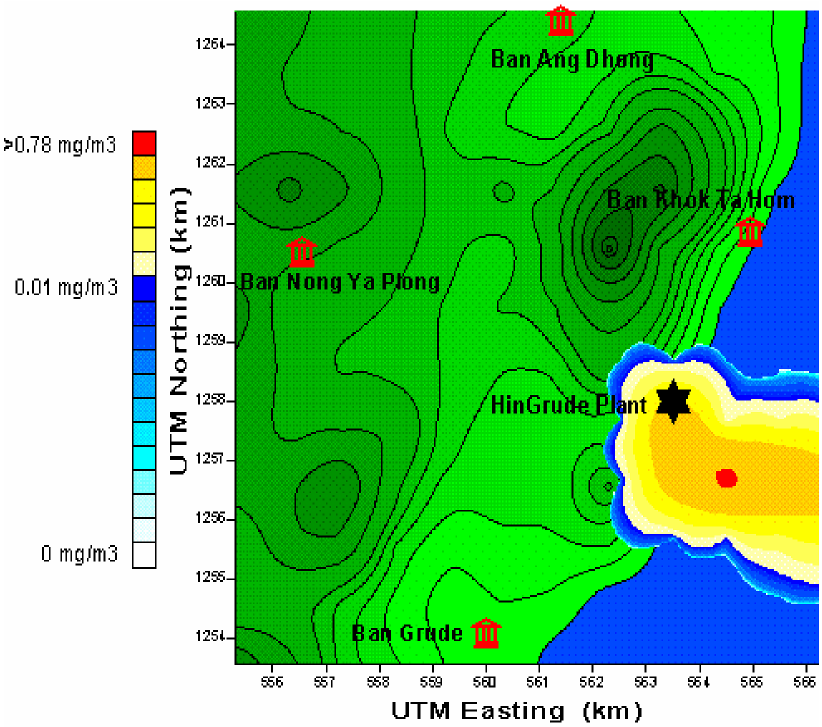


Figure 19 17th hour dispersion of SO_2 in winter

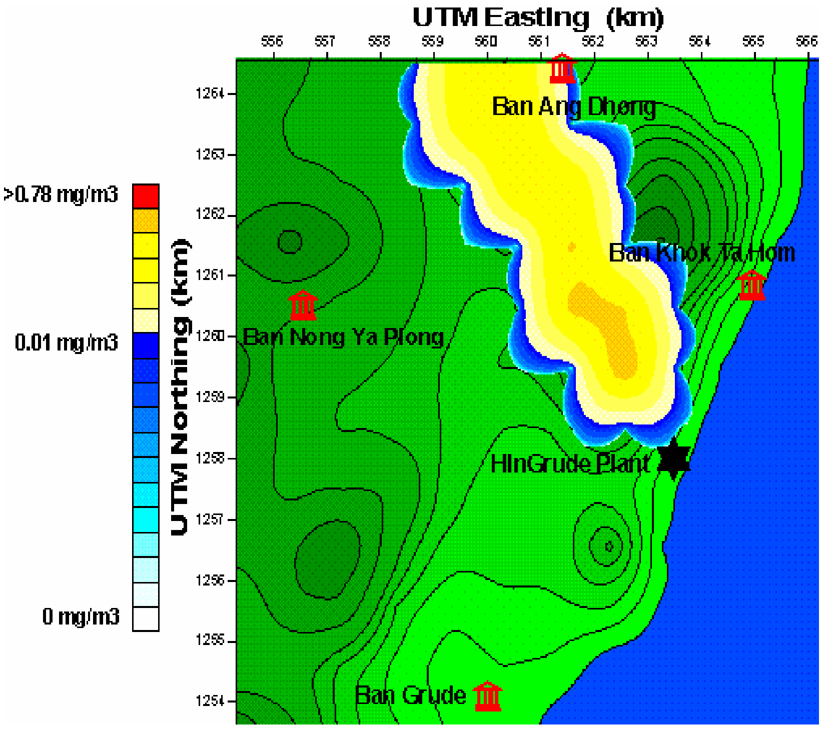


Figure 20 17th hour dispersion of SO_2 in summer

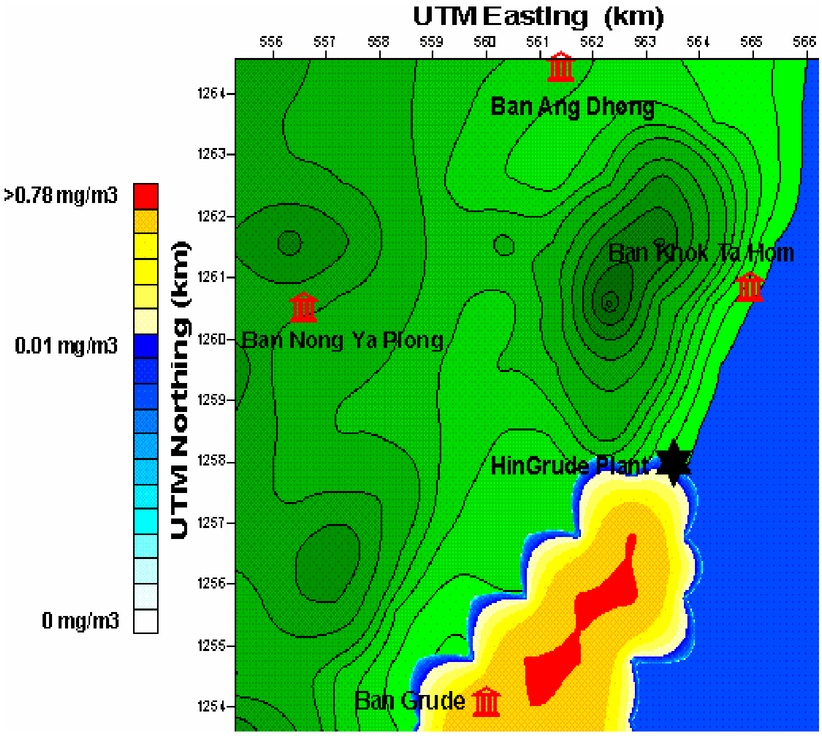


Figure 21 24th hour dispersion of SO_2 in rainy season

Below are examples of dispersion figures for NO_2 showing the influence of metrological conditions on the dispersion and concentrations of the pollutants released from Hingrude coal-fired power plant.

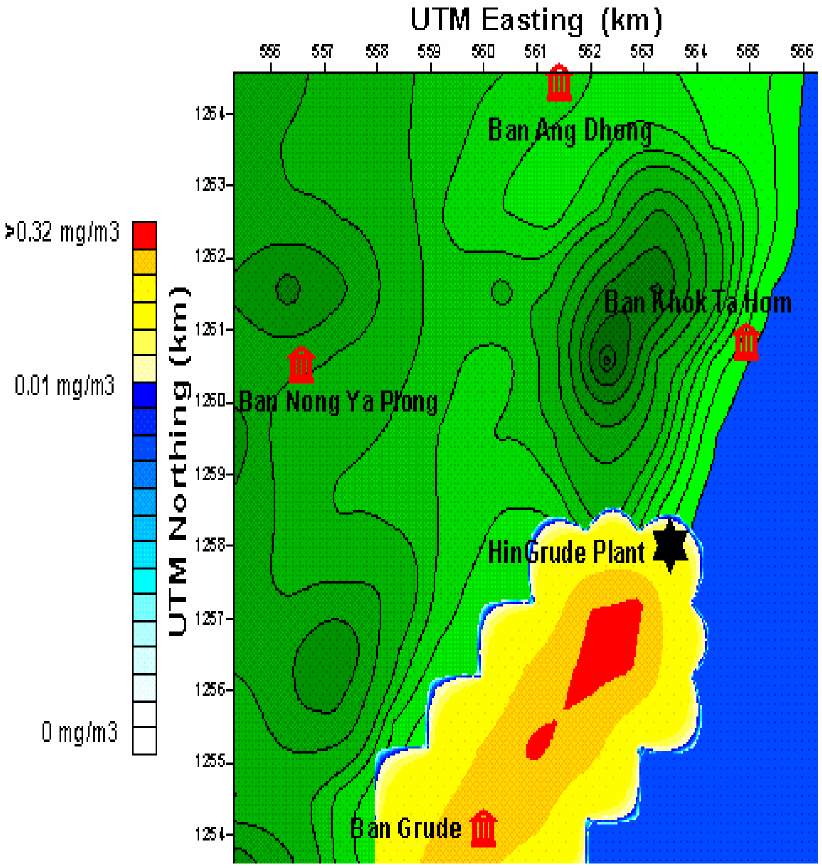


Figure 22 21st hour dispersion of NO_2 in rainy season

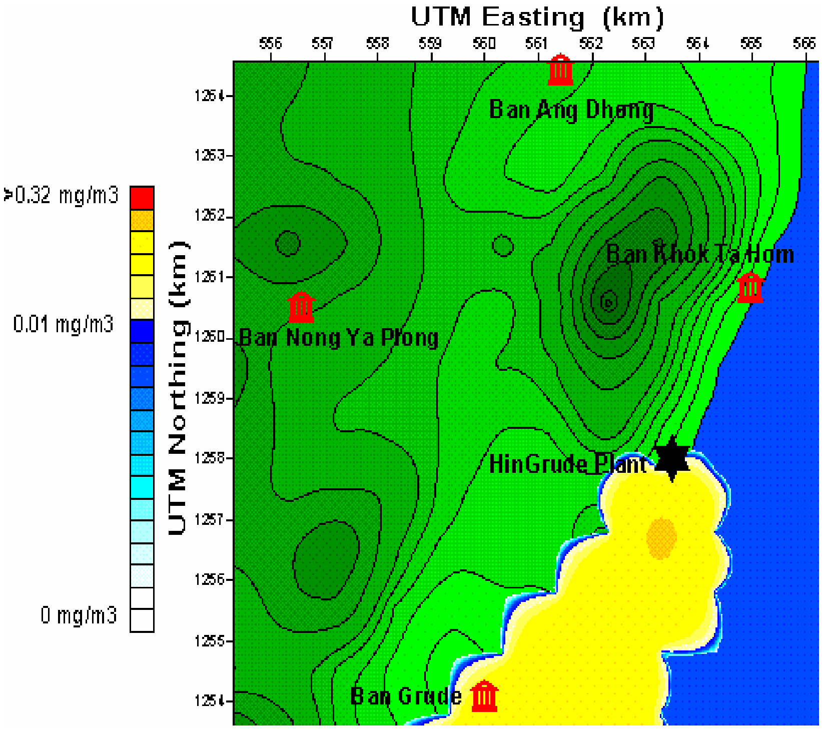


Figure 23 22nd hour dispersion of NO_2 in rainy season

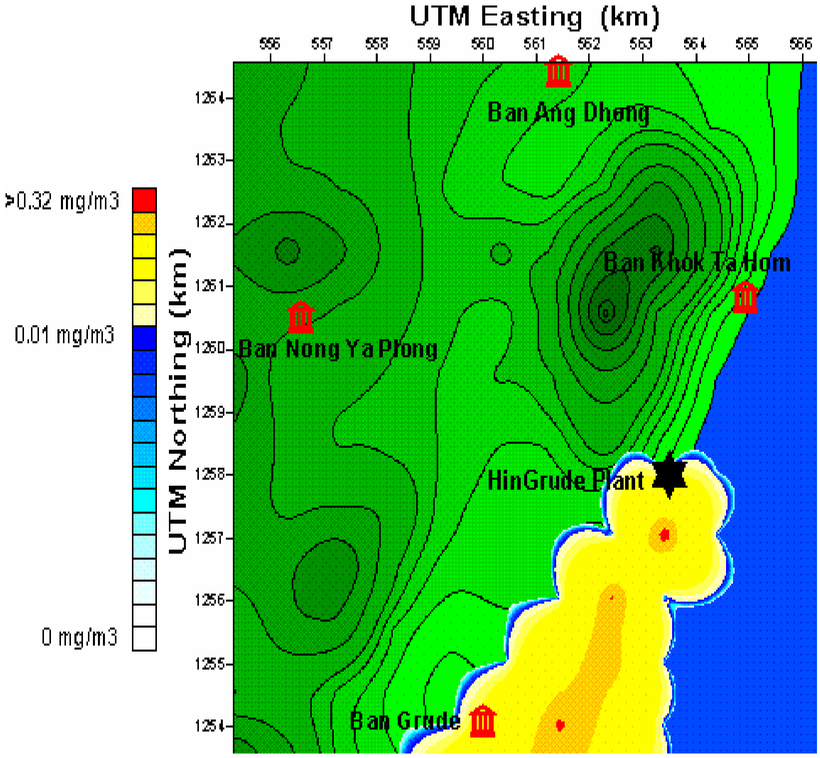


Figure 24 23rd hour dispersion of NO_2 in rainy season

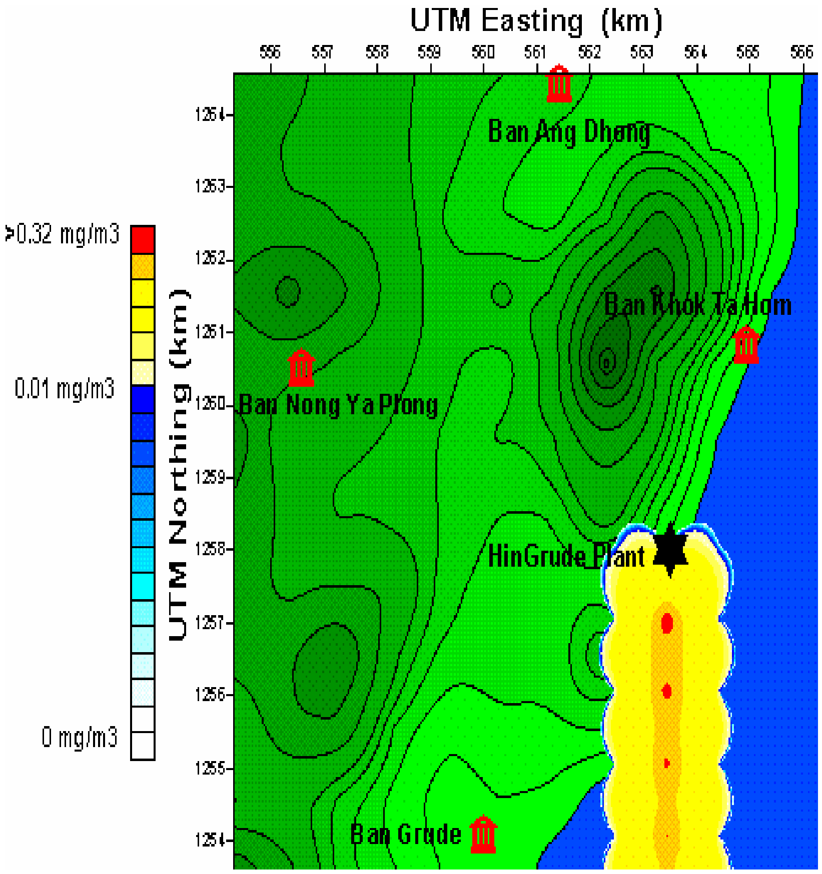


Figure 25 24th hour dispersion of NO_2 in rainy season

Discussion

1. Air Quality Impacts of Hingrude Coal-Fired Power Plant

From Table 12, it can be seen that the average concentrations of each air pollutant at four villages near Hingrude coal-fired power plant vary significantly. For example, the average 1-hour concentrations of SO_2 at four villages vary from 0.060139 x10^{-2} mg/m^3 to 0.15191 x10^{-1} mg/m^3 while the average 8-hour concentrations of CO range from 4.9165 x10^{-4} mg/m^3 to 1.7536 x10^{-3} mg/m^3. The possible key factors to this result are as follows:

1.1 Locations of villages

The locations of villages can contribute to the disparity in the concentrations of pollutants between four villages. Some locations may hinder the atmospheric dispersion of the pollutants whilst the others may not. For instance, if the village is on the mountain, the pollutants may not disperse through the village, thus resulting in low concentrations of the pollutants measured at the village. This could be used to justify why the concentrations of four pollutants at Ban Khok Ta Hom and Ban Ang Dhong located around the mountain or plateau, according to Figure 12, tend to be higher than those at other villages (When faced with the mountain or plateau, the pollutants tend to disperse around the mountain passing through both villages.).

1.2 Distances between villages and the plant

Basically, the further the pollutant disperses from the source, the lower its concentration is. This reinforces that the concentrations of the pollutant at distant villages should be lower than those of near villages, but the distance between the plant and village is not the sole factor affecting the concentrations of the pollutants at villages. Hence, other factors should be taken into consideration as well when comparing the concentration of each pollutant between four villages. For example, the average 1-hour concentration of SO_2 at Ban Khok Ta Hom (3.97 km from Hingrude coal-fired power plant) is higher than that at Ban Grude (5.31 km from the plant), but it is lower than that at Ban Ang Dhong (4.26 km from the plant).

1.3 Meteorological conditions

Meteorological conditions (e.g. wind speed, wind direction, mixing height, air pressure, air temperature, etc.) in the area of the plant do influence the dispersion of the pollutants released. For instance, if the wind speed is high, the pollutant can disperse farther than when the wind speed is low. Therefore, the concentrations of the pollutants at the villages with distinct meteorological conditions are most likely different, justifying the disparity in the concentrations of the pollutants between four villages, as can be seen in the above table.

1.4 Dispersion characteristics of air pollutants

Like metrological conditions, dispersion characteristics of the pollutants influence their dispersion. Each pollutant has different dispersion characteristics; some can disperse farther than the others in the same condition. Thus, the concentrations of different pollutants in the same village could differ. This could be an explanation of why the average concentrations of the pollutants at each village are different, as can be seen in Table 12.

From Table 12, it is obvious that the average concentrations of SO_2, CO, NO_2 and PM_{10} at four villages are all lower than the ambient air standards of Thailand. This reflects that the air quality impacts of these four pollutants on people residing in the four villages nearest Hingrude coal-fired power plant is considered acceptable. Given only these four air pollutants, it is therefore apparent that the air quality impacts of Hingrude coal-fired power plant on people in the four villages are negligible. However, the air quality impacts of these air pollutants in the area closer to Hingrude coal-fired power plant may be not acceptable as the average concentrations of these air pollutants in this area could be higher than the ambient air standards of Thailand.

Although the air quality impacts of the pollutants on people in four villages near Hingrude coal-fired power plant are found negligible, further investigation into the potential for adverse effects of 27 pollutants on the villagers to occur is still required. This is because the determination of the air quality impacts of the pollutants emitted is always done in EIA for coal-fired power plant, and the results tend to shows the acceptable air quality impacts of the pollutants to local people as well. Nonetheless, local people in many countries still suffer from air pollution contributed from the operation of coal-fired power plants. Consequently, the calculation of human health risks from 27 pollutants emitted from Hingrude coal-fired power plant to people residing in these four villages was done following the determination of the air quality impacts.

2. Human Health Risk Estimation

From Table 16, it can be seen that only 10 pollutants out of 27 pollutants have carcinogenic risks to local people in four villages. These pollutants include arsenic, beryllium, cadmium, chromium, 2,3,7,8-TCDD, lead, nickel, benzo(a)pyrene, benzene, carbon tetrachloride, chloroform and vinyl chloride. On the other hand, 22 out of 27 pollutants are found to pose non-carcinogenic risks to people in four villages, according to Table 17. These include ammonia, antimony, arsenic, barium, beryllium, carbon monoxide, chromium, cobalt, copper, hydrogen chloride, lead, manganese, mercury, nitrogen dioxide, benzo(a)pyrene, naphthalene, PM_{10}, selenium, sulfur dioxide, benzene, vinyl chloride and xylene.

This shows that just about half of 27 pollutants tested in this study (12 of 27 pollutants) are probable carcinogens in human whereas almost all of the pollutants tested (22 of 27 pollutants) are considered to have non-carcinogenic effects on human health. However, it does not necessarily mean these pollutants are not likely to cause adverse effects on human health. This is because SF or RfD values for these pollutants might not have been developed yet, or there have been inadequate information/evidence to develop them so far.

As both carcinogenic and non-carcinogenic risks of the pollutants were derived from the combination of their maximum 24-hour concentrations obtained from running CALPUFF modeling model, and other parameters (e.g. exposure duration, exposure frequency, and SF & RfD values), the degree of the risks vary according to the maximum 24-hour concentrations of the pollutants, considered other parameters constant. From Table 16 and Table 17, it is found that Ban Khok Ta Hom has the highest carcinogenic risks and non-carcinogenic risks of each of 27 pollutants, followed by Ban Nong Ya Plong, Ban Ang Dhong and Ban Grude, respectively. This reinforces that the maximum 24-hour concentrations of each of 27 pollutants were found highest in Ban Khok Ta Hom, followed by Ban Nong Ya Plong, Ban Ang Dhong and Ban Grude, respectively, as can be seen in Table 13.

From Table 18, the total carcinogenic risks of 27 pollutants to people in Ban Khok Ta Hom, Ban Ang Dhong, Ban Nong Ya Plong, and Ban Grude are 1.1778 x10^{-6}, 4.2719 x10^{-7}, 5.0106 x10^{-7} and 2.7429 x10^{-7}, respectively. Most of these total carcinogenic risks are less than 10^{-6} (U.S. EPA's acceptable carcinogenic risk level), thus making them acceptable to people in three villages: Ban Ang Dhong, Ban Nong Ya Plong and Ban Grude, with the exception of Ban Khok Ta Hom. However, the total non-carcinogenic risks to people in these four villages are 11.9030, 4.1062, 4.6873 and 2.7550, respectively, and all of them are considered unacceptable as they all exceed 1 (U.S. EPA's acceptable non-carcinogenic risk level), as can be seen in Table 19.

This means that 27 air pollutants emitted from Hingrude coal-fired power plant are likely to cause non-carcinogenic effects on people residing in the four villages near the plant. Nevertheless, the likelihood for these villagers to develop cancer as a result of inhaling these 27 air pollutants is considered low, with the exception of people residing in Ban Khok Ta Hom. Therefore, noncarcinogenic risk mitigation measures for people in these four villages and carcinogenic risk monitoring system for people in Ban Khok Ta Hom should be developed and provided within EIA for Hingrude coal-fired power plant.

The possible reason for this result is that only less than half of all pollutants tested in this study (12 out of 27) were found carcinogen or probable carcinogen, but nearly all of them (22 out of 27) are considered hazardous to human health. Also, it can be said that amongst these four villages, people in Ban Khok Ta Hom are found to have the highest possibility of having health problems and developing cancer, followed by people in Ban Nong Ya Plong, Ban Ang Dhong and Ban Grude, according to their total carcinogenic and non-carcinogenic risk levels shown in Table 18 and Table 19.

According to Table 12, the air quality impacts of 27 air pollutants emitted from Hingrude coal-fired power plant on people in four villages were found negligible; however, the results in Table 19 point out that these 27 pollutants are likely to cause adverse effects on people in these four villages. This highlights that even though air quality impacts caused by air pollutants released from the plant is considered acceptable, human health risk assessment should be done as well, because it is possible that the risks are found unacceptable to local people. Other pollutants, apart from NO_2, PM_{10} and SO_2, should also be investigated in EIA for coal-fired power plant, including Hingrude coal-fired power plant, because only NO_2, PM_{10} and SO_2 are usually examined in the EIA, but in fact there are at least 27 pollutants released from a typical coal-fired power plant, as can be seen in Table 3.

3. Human Health Risk Ranking

From Table 20 and Table 21, it can be seen that most pollutants have the same risk rankings for four villages, with a few pollutants having different risk rankings for four villages. For instance, beryllium is found to cause the third highest carcinogenic risks to people in four villages, and it has the seventh non-carcinogenic risk ranking for four villages. On the other hand, non-carcinogenic risks contributed from PM_{10} are ranked the second highest for three villages (Ban Khok Ta Hom, Ban Nong Ya Plong and Ban Grude), but it is found to cause the sixth highest non-carcinogenic risks to people in Ban Ang Dhong.

Some pollutants e.g. ammonia, carbon monoxide, chloroform and nickel, do not have either carcinogenic risk ranking or non-carcinogenic risk ranking, as can be seen in Table 20 and Table 21. This is because carcinogenic or non-carcinogenic risks of these pollutants could not be calculated resulting from the unavailability of their SF or RfD values.

According to Table 22 and Table 23, metallic pollutants tend to have high risk rankings in both carcinogenic and non-carcinogenic risk rankings. For example, beryllium was ranked the second and seventh in Table 22 and Table 23, respectively.

This shows that metallic pollutants are the main contributors to carcinogenic and non-carcinogenic risks to people in villages near Hingrude coal-fired power plant.

In particular, five top ranked pollutants in carcinogenic risk ranking are all metallic pollutants. These include nickel, cadmium, beryllium, chromium and arsenic. This reflects that amongst 27 pollutants tested in this study, metallic pollutants are found to pose highest carcinogenic risks to people in villages near Hingrude coal-fired power plant. The main cause for this could be the high level of their carcinogenic hazards, as can be seen from the high values of their SFs compared to those of volatile organic compounds and polycyclic hydrocarbons in appendix G.

On the other hand, volatile organic compounds and polycyclic hydrocarbons are considered to pose least both carcinogenic and non-carcinogenic risks to local people as they were ranked very low in both Table 22 and Table 23. For instance, benzo(a)pyrene was ranked lowest in both carcinogenic and non-carcinogenic rankings (12th for carcinogenic risk ranking and 22th for non-carcinogenic risk ranking). This could result from their low emission rates, low degree of health hazards or dispersion characteristics.

Although metallic pollutant, e.g. barium, manganese and beryllium, are ranked high in both Table 22 and Table 23, top ranked pollutants in non-carcinogenic risk ranking are NO_2, PM_{10}, SO_2 and hydrogen chloride, not metallic pollutants. An explanation for this could be the high emission rates for these pollutants (600 g/s for NO_2, 52.084 g/s for PM_{10}, 1170 g/s for SO_2 and 63.0561 g/s for hydrogen chloride). However, other factors, such as dispersion characteristics and RfD values, may have the influence on this non-carcinogenic risk ranking as well.

As explained before, some pollutants were ruled out when conducting either carcinogenic or non-carcinogenic risk ranking, because SF or RfD values for these pollutants are not available. If SF or RfD values for these pollutants were available, they would be included within human health risk rankings, either carcinogenic or non-carcinogenic, and as a result the ranking of pollutants in Table 22 and Table 23 could be altered. Therefore, the results of human health risk rankings shown in Table 22 and Table 23 could be erroneous.

4. Risk Estimation for Top Ranked Air Pollutants

From Table 25, it can be seen that the total non-carcinogenic risks of three top ranked pollutants (NO_2, PM_{10} and SO_2) for Ban Khok Ta Hom, Ban Ang Dhong, Ban Nong Ya Plong and Ban Grude are 10.8350, 3.7378, 4.2668 and 2.5079, respectively. These total non-carcinogenic risks are all higher than 1 (U.S. EPA's acceptable non-carcinogenic risk level) meaning that the total non-carcinogenic risks of NO_2, PM_{10} and SO_2 are unacceptable to people in four villages near Hingrude coal-fired power plant or these pollutants are likely to cause adverse effects on people in four villages.

From Table 26, it can be said that the total non-carcinogenic risks of 24 pollutants are all lower than 1 (U.S. EPA's acceptable non-carcinogenic risk level) reflecting that without NO_2, PM_{10} and SO_2, the remaining pollutants (24 pollutants) are not likely to pose threat to people in four villages near the plant. Hence, it can be concluded that NO_2, PM_{10} and SO_2 are the main contributors to non-carcinogenic risks to people in four villages near Hingrude coal-fired power plant. In other words, the level of the total non-carcinogenic risks of 27 pollutants emitted from coal-fired power plant is highly dependent on non-carcinogenic risks contributed from NO_2, PM_{10} and SO_2.

In EIA for coal-fired power plant, including Hingrude coal-fired power plant, the air quality impacts of NO_2, PM_{10} and SO_2 are usually examined and checked, and the results tend to show that the air quality impacts are acceptable or negligible, but risk assessment has never been done for these pollutants in the EIA for coal-fired power plant. However, the human health risk assessment for NO_2, PM_{10} and SO_2 was done in this study, and the results reveal that these pollutants are likely to cause health problems to people in four villages near Hingrude coal-fired power plant, as can be seen in Table 25. This once again highlights that even though air quality impacts caused by air pollutants released from the plant is considered acceptable, human health risk assessment should be done as well, because it is possible that the risks are found unacceptable to local people. Because of this, it can be said that only determining air quality impacts of pollutants emitted from the plant is apparently inadequate in EIA for coal-fired power plant. Hence, human health risk assessment should be included within the process of EIA for coal-fired power plant (including Hingrude coal-fired power plant), ensuring the potential for air pollutants emitted to cause carcinogenic and non-carcinogenic effects on local people. This could be an explanation of why local people in many countries are badly affected by air emission contributed from coal-fired power plants even though EIA for these plants has been approved already.

5. Dispersion of Top Ranked Air Pollutants

From Figure 13 to Figure 21, it can be seen that the dispersion of three pollutants (NO_2, PM_{10} and SO_2) in three seasons (winter, summer and rainy season) is similar. These three pollutants tend to disperse southeast from Hingrude coal-fired power plant in winter while they move northwest in summer. In rainy season, these pollutants are likely to disperse from the plant to west or southwest. This implies that the direction of the dispersion for the pollutants is apparently dependent upon meteorological condition of the area, particularly wind direction, and types of pollutants seem to have no or not much influence on the direction of their dispersion.

According to all the dispersion figures in appendix J, it can be said that the concentrations of the pollutants (NO_2, PM_{10} and SO_2) emitted from Hingrude coal-fired power plant are initially represented by blue color; or their concentrations are low. However, as time goes, the concentrations increase significantly as a result of the continuous release of the pollutants. When the concentrations of the pollutants approach the ambient air standards used, the dispersion of the pollutants in the figures are represented by yellow color, or the concentrations of the pollutants are high. Blue and yellow colors both indicate that the concentrations of the pollutants are acceptable to people in the area. Once the concentrations of the pollutants exceed the ambient air standards used (0.32 mg/m^3 for NO_2, 0.15 mg/m^3 for PM_{10} and 0.78 mg/m^3 for SO_2), they are considered to cause adverse effects on people in the area, and thus red color is used to represent the dispersion of the pollutants.

From all the dispersion figures in appendix J, it can be seen that red color or dangerous area for the dispersion of three pollutants tends to appear near Hingrude coal-fired power plant, and it never covers the area of four villages near the plant. This indicates that four villages (Ban Khok Ta Hom, Ban Ang Dhong, Ban Nong Ya Plong and Ban Grude) near Hingrude coal-fired power plant are all in safe area or sensitive area, not dangerous area. In other words, the air quality impacts of NO_2, PM_{10} and SO_2 released from Hingrude coal-fired power plant are acceptable to people in four villages near the plant. However, this could be subject to some factors e.g. meteorological conditions.

From Figure 22 to Figure 25, it can be seen that the direction of the dispersion for NO_2 in rainy season change from southwest in 21st hour to south in 24th hour due possibly to change in meteorological condition, especially wind direction. Furthermore, Figure 22 shows large area of red color (dangerous area) in southwest area of Hingrude coal-fired power plant but it disappears in Figure 23, and only some small red colors reappear in Figure 24 and Figure 25 where the dispersion of NO_2 moves from southwest to south.

A possible explanation for this is that there are some changes in metrological conditions in this area between 21st hour and 24th hour. For example, wind direction is altered, thus changing the direction of the dispersion for the pollutant. If mixing height is changed, the pollutant will also mix together at different level affecting the level of its concentrations in dispersion. This reflects that the dispersion, concentrations and even the air quality impacts of the pollutants emitted from Hingrude coal-fired power plant seem to be dependent on meteorological conditions. Therefore, it can be said that even though the concentrations of the pollutants released from the plant increase or the red color areas expand as time goes, they may decline or shrink if the meteorological conditions, e.g. mixing height and wind direction, in the area change.

CONCLUSION AND RECOMMENDATION

Conclusion

In summary, the study reveals that there are at least 108 pollutants found in air emission from a typical coal-fired power plant. These pollutants include polycyclic aromatic hydrocarbons, metallic pollutants, volatile organic compounds and traces gases, as shown in Table 1. Owing to availability of U.S. EPA's coal combustion emission factors and SFs & RfDs, and half life of the pollutants, only 27 pollutants listed in Table 3 were examined and tested in this study. However, only three pollutants (NO_2, PM_{10} and SO_2) are usually investigated in EIA for coal-fired power plant, including Hingrude coal-fired power plant. Because of this, investigating only these three pollutants in EIA for coal-fired power plant seems to be not sufficient, and therefore more pollutants should be examined and studied within the EIA for coal-fired power plant, including Hingrude coal-fired power plant.

The air quality impacts and carcinogenic risks of 27 pollutants tested in CALPUFF modeling system were found acceptable to people residing in four villages nearest Hingrude coal-fired power plant as they are all lower than U.S. EPA's carcinogenic risk acceptable level and ambient air standards of Thailand, with the exception of carcinogenic risks to villagers in Ban khok Ta Hom. Nonetheless, these 27 pollutants were considered to be likely to cause non-carcinogenic effects on people in these four villages, because the total non-carcinogenic risks of these pollutants are higher than U.S. EPA's non-carcinogenic acceptable risk level. This highlights that even though the air quality impacts of pollutants emitted from coal-fired power plant is found acceptable to local people, their human health risks may be unacceptable to local people. Hence, human health risk assessment should be included within the process of EIA for coal-fired power plants. However, it has never been included within EIA for coal-fired power plants, including Hingrude coal-fired power plant, justifying why local people in many countries are apparently affected by air pollution contributed from a coal-fired power plant even though its EIA has been approved already. This also applies to the case of Hingrude coal-fired power plant where local people have been resisting its construction for the past ten years although its EIA has been approved for a long time.

Human health risk ranking conducted represents that metallic pollutants e.g. cadmium, nickel and beryllium were found to pose high carcinogenic risks to people in four villages near Hingrude coal-fired power plant due possibly to high SF values while NO_2, PM_{10} and SO_2 were ranked top in non-carcinogenic risk ranking potentially because of their high emission rates. On the other hand, volatile organic compounds and polycyclic hydrocarbons, e.g. benzo(a)pyrene and vinyl chloride, were found to contribute to least both carcinogenic and non-carcinogenic risks to local people as they were ranked very low in both carcinogenic and non-carcinogenic risk ranking. This could be because of their low emission rates, low degree of health hazards or dispersion characteristics.

It is found that amongst 27 pollutants tested in this study, NO_2, PM_{10} and SO_2 are the main contributors in non-carcinogenic risks to people in four villages near Hingrude coal-fired power plant. The total non-carcinogenic risks of these three pollutants are also found unacceptable to people in four villages. It is therefore recommended that human health risk assessment be conducted for NO_2, PM_{10} and SO_2 following the determination of their air quality impacts, and risk mitigation measures need to be developed and provided in EIA for Hingrude coal-fired power plant if calculated risks are unacceptable.

The study also highlights that the dispersion of the pollutants released from coal-fired power plant is dependent upon several factors. These factors include metrological conditions in the area of the plant (mixing height, wind direction, wind speed, etc.), dispersion characteristics of pollutants and their emission rates. These factors therefore need to be taken into consideration when investigating dangerous area around coal-fired power plant (area where the concentrations of the pollutants are higher than the ambient air standards). However with respect to the direction of the dispersion of the pollutants emitted from the plant, metrological conditions, especially wind direction, are the only influential factor, excluding types of pollutants.

Recommendation

Some suggestions for better use of this research results in the future are made below. These recommendations were provided based upon limitations of the research study, such as no field sampling and limited number of data collected.

1. As emission rates used in this study were calculated based upon U.S. EPA's coal combustion emission factors which were the average emissions of certain pollutants per volume of coal burned (not actual emission rates), the concentrations of the air pollutants obtained from CALPUFF modeling system could be erroneous. Therefore, further study to determine air quality impacts and human health risks based upon field sampling & laboratory test for a coal-fired power plant in operation should be done as well so that the disparity in the results between these two methods (air dispersion model and field sampling & laboratory test) can be drawn, and the model can be calibrated then.

2. According to U.S. EPA, five years meteorological data is a minimum requirement for running an air dispersion model, but only one year meteorological data was used in this study. Because of this, the results of the study may contain some errors, and thus further study to run CALPUFF modeling system based upon five years metrological data is required for better use of the results.

3. As U.S. EPA's coal combustion emission factors used to calculate emission rates of the pollutants in this study were derived from the researches on coal-fired power plants in the USA, some errors may rise when applying them to determine air quality impacts and human health related risks of air pollutants emitted from coal-fired power plant in Thailand, for example, Hingrude coal-fired power plant. Hence, more studies using emission factors from other countries, particularly Thailand should be carried out later prior to practical use of the research results.

LITERATURE CITED

Agency for Toxic Substances and Disease Registry. 2005. **CERCLA Priority of Hazardous Substances and Toxicity of Substances**. Department of Health and Human Services, Atlanta.

Arthur, C.S. 1976. **Air Pollution**: Air Pollutants, their Transformation and Transport. 3rd ed. Academic Press, Inc., New York.

Berkowitz, N. 1994. **An Introduction to Coal Technology**. 2nd ed. Academic Press, Inc., California.

Blazej, N. 2004. **Air Toxics Risk Assessment Reference Library: Technical Resource Manual**. U.S. Environmental Protection Agency, Washington.

British Columbia Ministry of Environment. 2006. **Guidelines for Air Quality Dispersion Modeling in British Columbia**. Academic Press, Inc., Vancouver.

Carpenter, M.A., S. Niksa., D.H. Scott. and Z. Wu. 2007. **Fundamentals of Coal Combustion**. IEA Clean Coal Centre, London.

Clean Manufacturing Technology Institute. 2007. **Indiana Relative Chemical hazard Ranking System and Chemical Health Hazards**. Purdue University, Indiana.

Durham, M. 2006. **Air Dispersion Modeling: ISCST3 VS AERMOD**. Stanley Consultants, Inc., Iowa.

Godish, T. 2004. **Air Quality**. 4th ed. CRC Press LLC, Florida.

Hall, G. 2005. **Guideline on Air Quality Models: Adoption of a Preferred General Purpose (Flat and Complex Terrain) Dispersion Model and Other Revisions; Final Rule**. U.S. Environmental Protection Agency, Washington.

Hall, N. 1990. **National Ambient Air Quality Standards**. The Clean Air Act. Available Source: http://epa.gov/air/criteria.html, May 16, 2007.

Harold, J.R. 1998. **ODOR and VOC Control Handbook**. McGraw-Hill, Inc., New York.

Heath, D., G. Kim., S. Mustafa. and E. Peters. 2006. **Air Dispersion Modeling Guideline**s. New Mexico Air Quality Bureau, New Mexico.

Howard, B. and H. Sara. 2006. **Application of AERMOD and CALPUFF Models for Power Plant Permitting in the MDAQMD**. Academic Press, Inc., California.

Howard, E.H. 1996. **Air Pollution Control Traditional and Hazardous Pollutants**. Technomic Publishing Company, Inc., Pennsyvania.

Howard, H.F. 1988. **Hazardous and Toxic Materials Safe handling and Disposal**. 2nd ed. Jon Wiley&Sons, Inc., New York.

Idriss, A. 2003. **Air Quality Guideline**. Alberta Environment, Toronto.

Jirungnimitasaku, S. and J. Kreasuwan. 2004. **Application of CALPUFF Model on Sulfur Dioxide Dispersion from Mae Moh Power Plant**. M.S. Thesis, Chiang Mai University.

Keating, M. 2001. **Cradle to Grave: The Environmental Impacts from Coal**. Clean Air task Force, Boston.

Kolluru, R.V., S.M. Bartell., R.M. Pitblado. and R.S. Stricoff. 1996. **Risk Assessment and Management Handbook for Environmental Health and Safety Professionals**. McGraw-Hill, Inc., New York.

Louvar, J.F. and B.D. Louvar. 1998. **Health and Environmental Risk Analysis Fundamentals with Applications**. Prentice-Hall, Inc., New Jersey.

Manning, C. 1993. **Compilation of Air Pollutant Emission Factors**. U.S. Environmental Protection Agency, Washington.

Markuszewski, R. and B.D. Blaustein., 1986. **Fossil Fuels Utilization**. American Chemical USA Society, Miami.

Mauch, S. 2005. **Air Dispersion Modeling**. Weston Solutions, Inc., Arizona.

Merrich, D. 1984. **Coal Combustion and Conversion Technology**. Malmillian Publisher Ltd., Hong Kong.

Ministry for the Environment of New Zealand. 2004. **Good Practice Guide for Atmosphere Dispersion Modeling**. Wilson and Horton Ltd., Wellington, New Zealand.

National Pollutant Inventory. 2007. **Substance Fact Sheet**. Department of the Environment, Water, Heritage and the Arts, Canberra.

North Carolina Department of Environment and Natural Resources. 2007. **Emission Factors**. North Carolina Division of Air Quality Progress Report. Available Source: daq.state.nc.us/Calendar/Planning/MarchAQC/AGENDAITEM%209.pdf, August 28, 2007.

Panich, N. and S. Panich. 2001. **An Overview of Air Quality Mathematical Model**. Chulalongkorn University Press., Bangkok.

Richard, J.F., 1999. **Environmental Risk Assessment Report for Hingrude Coal-Fired Power Plant**. Sangsan Consultants Limited, Bangkok.

Robert, H.J. and K.L. Robert., 1999. **Sources and Control of Air Pollution**. Prentice-Hall, Inc., New Jersey.

Roger, S. 2006. **Coal Outlook**. Coal Utilization. Available Source: http://geo-tec.net/coal_outlook.htm, April 10, 2007.

Scire, J.S., D.G. Strimaitis. and R.J. Yamartino. 2000. **A User's Guide for the CALPUFF Dispersion Model and CALMET Meteorological Model**. Earth Tech, Inc., Massachusetts.

Surapipith, V. 2006. **Application of CALPUFF Modeling System**. Pollution Control Department, Bangkok.

The U.S. Department of Energy. 2007. **Fossil Fuel**. Coal. Available Source: www.eia.doe.gov/kids/energyfacts/sources/non-renewable/coal.html, April 3, 2007.

University of Tennessee. 2005. **Toxicity Values**. Toxicity Profile. Available Source: http://rais.ornl.gov/tox/rap_toxp.shtml, June 15, 2007.

Wright, D.A. and P. Welbourn. 2002. **Environmental Toxicology**. Cambridge University Press, Inc., Cambridge.

APPENDICES

Appendix A

Detailed information on Hingrude coal-fired power plant

This section contains one table and one picture. The table illustrates detailed information on proposed Hingrude coal-fired power plant. This information includes number of workers, size of the plant, operation duration, capacity and location. The picture shows the proposed location of Hingrude coal-fired power plant.

Appendix Table A1 Detailed information on proposed Hingrude coal-fired power plant

Detailed Information on Proposed Hingrude Coal-Fired Power Plant	
Name	Hingrude Coal-Fired Power Plant
Capacity	1400 MW
Number of workers	200 employees approximately
Location	Bang Sapan district, Prachuap Khiri Khan, Thailand
Coordinate for location	Latitude: 11°23’37.47” N Longitude: 99° 33’40.90” E, 3.5 km to coastal area
Operation duration	365 days/year except for maintenance period
Size	1,600,000 m^2
Concessionaire	Union Power Development limited
Concession period given	25 years
Type of coal used	Subbituminous coal
Coal origin	Australia, Indonesia and South Africa
Coal transportation	Shipping
Annual coal usage	3.75 million tons or 10,000 tons per day
Date EIA submitted	26 March, 1997
Date EIA approved	29 May, 1998
Construction commencement	1 April, 1999
Construction duration	4 years
Near villages	1. Ban Ang Dhong: 4.2 km to north 2. Ban Khok Ta Hom: 3.5 km to east 3. Ban Grude: 5.3 km to south 4. Ban Nong Ya Plong: 4.5 km to west

Appendix Table A1 (Continued)

Detailed Information on Proposed Hingrude Coal-Fired Power Plant	
Stack height	200 m
Stack diameter	8 m
Exit velocity	18.7 m/s
Exit temperature	373°K
Air pollution control equipment	1. Flue gas desulphurization (FGD) for SO_2 2. Electrostatic precipitators (ESP) for particulate matter 3. Enhanced-Ignition dual-register babcock for NO_x 4. Others
Monitoring equipment	Continuous Emissions Monitoring System

Source: Richard (1999)

Appendix Figure A1 Proposed location of Hingrude coal-fired power plant

Appendix B

Detailed information on coal

1. Coal

Coal is a fossil fuel formed in swamp ecosystems where plant remains were saved by water and mud from oxidation and biodegradation. Coal is a readily combustible black or brownish-black rock. It is a sedimentary rock, but the harder forms, such as anthracite coal, can be regarded as metamorphic rocks because of later exposure to elevated temperature and pressure. It is composed primarily of carbon along with assorted other elements, including sulfur. It is the largest single source of fuel for the generation of electricity worldwide, as well as the largest source of carbon dioxide emission, which have been implicated as the primary cause of global warming. Coal is extracted from the ground by coal mining, either underground mining or open-pit mining.

2. Origin of Coal

Coal was formed in swamp ecosystems which persisted in lowland sedimentary basins similar, for instance, to the peat swamps of Borneo today. These swamp environments were formed during slow subsidence of passive continental margins, and most seem to have formed adjacent to estuarine and marine sediments suggesting that they may have been in tidal delta environments. They are often called the “coal forests”.

When plants die in these peat swamp environments, their biomass is deposited in anaerobic aquatic environments where low oxygen levels prevent their complete decay by bacteria and oxidation. For masses of undecayed organic matter to be preserved and to form economically valuable coal the environment must remain steady for prolonged periods of time, and the waters feeding these peat swamps must remain essentially free of sediment. This requires minimal erosion in the uplands of the rivers which feed the coal swamps, and efficient trapping of the sediments.

Eventually, and usually due to the initial onset of other tectonic events, the coal forming environment ceases. In the majority of cases this is abrupt, with the majority of coal seams having a knife-sharp upper contact with the overlying sediments. This suggests that the onset of further sedimentation quickly destroys the peat swamp ecosystem and replaces it with meandering stream and river environments during ongoing subsidence.

Burial by sedimentary loading on top of the peat swamp converts the organic matter to coal by the following processes;

2.1 Compaction, due to loading of the sediments on the coal which flattens the organic matter

2.2 Removal of the water held within the peat in between the plant fragments

2.3 With ongoing compaction, removal of water from the inter-cellular structure of fossilized plants

2.4 With heat and compaction, removal if molecular water

2.5 Methanogenesis; similar to treating wood in a pressure cooker, methane is produced which removes hydrogen and some carbon, and some further oxygen (as water)

2.6 Dehydrogenation, which removes hydroxyl groups from the cellulose and other plant molecules, resulting in the production of hydrogen-reduced coals.

Generally, to form a coal seam 1 meter thick, between 10 and 30 meters of peat is required. Peat has a moisture content of up to 90%, so loss of water is of prime importance in the conversion of peat into lignite, the lowest rank of coal. Lignite is then converted by dehydrogenation and methanogenesis to sub-bituminous coal. Further dehydrogenation reactions, removing progressively more methane and higher hydrocarbon gases such as ethane, propane, etcetera, create bituminous coal and, when this process is complete at sub-metamorphic conditions, anthracite and graphite are formed.

Evidence of types of plants that contributed to carbonaceous deposits can occasionally be found in the shale and sandstone sediments that overlie coal deposits and within the coal. Fossil evidence is best preserved in lignites and sub-bituminous coals, though fossils in anthracite are not too rare. To date only three fossils have been found in graphite seams created from coal.

3. Types of Coal

As geological processes apply pressure to peat over time, it is transformed successively into:

3.1 Anthracite

The hardest coal type, (often referred to as “hard coal”), contains a high percentage of fixed carbon and a low percentage of volatile matter. Anthracite is the highest rank coal and it contains about 90% fixed carbon, more than any other form of coal. Anthracite has a semi-metallic luster and is capable of burning with little smoke (smokeless fuel). It is used in domestic and industrial applications, but is the least plentiful of all the coals.

3.2 Bituminous coal

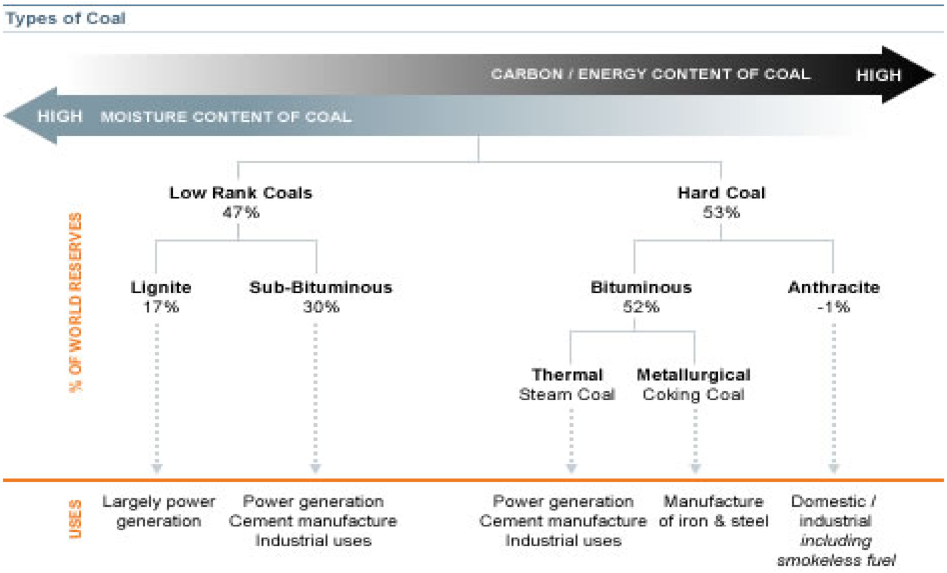
The most commonly used coal in the United States, it is soft, dense and black. Its moisture content usually is less than 20 percent. It is used for generating electricity, making coke, and space heating. Bituminous coal can be metallurgical (also known as coking coal) or thermal (also known as steam coal). Metallurgical/Coking coal is a coal which can be usefully converted into coke or one which gives a coke strong enough to resist pressure and breakage. The term coking coal covers a range of coals, the cokes from which serve different purposes depending primarily on the fixed carbon and volatile matter of the original coal. Thermal/Steam coal is a coal considered particularly suitable for boiler use, or power generation.

3.3 Lignite

Lignite is a brownish-black coal of low rank with high inherent moisture and volatile matter (used almost exclusively for electric power generation). It is also referred to as brown coal. It is characterized by its high moisture content and low carbon andenergy content compared to high rank coals such as anthracite. Due to its high moisture content and relatively low calorific value, lignite is usually consumed at or close to where it is produced or mined.

3.4 Subbituminous coal

Subbituminous coal is dull black and generally contains 20 to 30 percent moisture. The heat content of sub-bituminous coal ranges from 16 to 24 million Btu per ton and is used for generating electricity and space heating. Subbituminous coal is the next highest coal in rank after lignite and is softer than bituminous coal. Because it contains more moisture than bituminous coal, it less economic to transport long distance. The following picture illustrates the classification of coal and appropriate use for each type.



Appendix Figure B1 Classification of coal

Source: Roger (2006)

4. Specification of Coals from Different Countries

Composition and properties of coal vastly range from place to place due mainly to climate, geology, weathering processes, minerals and substances available. Therefore, the properties and composition of coal from countries differ from slightly to considerably. Below is the table representing the properties of typical coals from several countries.

Appendix Table B1 Typical properties of coal from several countries

Coal	**Heat Value Kcal/kg**	**Moisture %**	**Ash Content %**	**Volatile %**	**Carbon %**	**Sulfur %**
Australia	6300-6700	8-10	11.5-14.5	24-31	47-57	0.37-0.65
Indonesia	5200-6200	15-25	1-9	36-42	35-37	0.1-0.7
South Africa	6200-6450	8-8.5	12-13.5	20-25	53.8-55	0.6-0.75
China	4500-6000	3-23	28-33	6-15	50-81	0.4-3.7
India	3100-5000	4-15	30-50	-	-	0.2-0.7
Thailand	4300-5200	10-35	11-17	35-45	28-39	0.5-2
USA	3600-6700	13-30	4.5-9	31-41	50-54	0.6-4
Canada	3800-6700	18-26	11-15.4	5.85-25.9	43-75	0.33-1.1

Source: Roger (2006)

5. Use of Coal

About 70 percent of world’s coal consumption is for generating electricity with the rest of the coal is used, as a basic energy source in many industries, including, steel, cement and paper. The three major uses of coal are:

5.1 For electricity power

Coal is used to generate roughly half of the world's electricity. Besides electric utility companies, industries and businesses with their own power plants use coal to generate electricity. Power plants burn coal to make steam for turning turbine, which will in turn generating electricity.

5.2 For industry

A variety of industries use coal's heat and by-products. Separated ingredients of coal are used in making plastics, tar, synthetic fibers, fertilizers, and medicines. The concrete and paper industries also burn large amounts of coal.

5.3 For making steel

Coal is baked in hot furnaces to make coke, which is used to smelt iron ore into iron needed for making steel. It is the very high temperatures created from the use of coke that gives steel the strength and flexibility for products such as bridges, buildings, and automobiles (The U.S. Department of Energy, 2007).

6. Air Pollution from Coal Use

Air pollution cause by use of coal can be broken down into five major categories as shown below.

6.1 Smog and ozone

Power plants are second only to automobiles as the greatest source of NO_x emissions. When nitrogen oxide (NO_x) reacts with volatile organic compounds (VOCs) and sunlight, smog (ground level ozone) forms. Of the six major criteria air pollutants regulated by the U.S. EPA, NO_x emissions have historically been the hardest to control. One of the contributing factors is that NO_x emissions from huge dirty coal plants in one region can easily pollute areas hundreds of miles downwind.

When inhaled, smog can cause a wide range of health problems, including immediate symptoms like shortness of breath, chest pains, wheezing, and increased susceptibility to respiratory problems. Smog can also cause many more serious problems like increased risk of asthma attacks and lung inflammation. Recently, scientists concluded that exposure to smog can be deadly. Smog affects everyone, but is especially dangerous for children, the elderly, and those with respiratory problems.

Even our national parks have not escaped the smog and ozone pollution caused by coal-fired power plants. Many parks already experience unhealthy air days, and the problem is getting worse. Smog concentrations have increased at 22 of 31 National Park Service monitoring sites since 1990. This persistent ozone pollution can harm plants and vegetation by damaging leaves and disrupting growth. Along with other pollutants, nitrous oxides can also chemically alter soil and water, leading to acidification and other serious problems that harm plants and animals.

6.2 Particle pollution and soot

Coal-fired power plants are also the largest single source of sulfur dioxide (SO_2), releasing about 2/3 of the total SO_2 pollution each year. Sulfur dioxide, which can travel long distances in the atmosphere before falling down to the land, can cause problems on its own as well as when it combines with other pollution to form other dangerous compounds. In addition to acid rain (see below), SO_2 can combine with nitrogen oxide (NO_x) and other particles to form particulate matter, which is sometimes called soot. Particulate matter, which can also be released directly from the smokestacks of coal-fired power plants, is often divided into categories based on the size of the particles-coarse, fine, and ultrafine-but all three are hazardous to people health and the environment.

Particle pollution is one of the most dangerous air pollutants, and over 64 million Americans are estimated to breathe air that has so much particle pollution that it puts their health at risk. Particle pollution can trigger heart attacks and strokes, lead to cardiac arrhythmia (irregular heartbeat), cause respiratory irritation, and worsen asthma. Both short-term and long-term exposure can cause premature death. In fact, particle pollution from power plants in the U.S. leads to over 30,000 deaths each year- a shocking figure when compared to the 17,000 homicides committed each year. Cutting power plant emissions by 75% could avoid more than 18,000 of the deaths caused by particle pollution.

6.3 Acid rain

Acid rain, or acid deposition, occurs when sulfur dioxide (SO_2) and nitrogen oxide (NO_x) react with water and oxygen in the atmosphere to form acidic compounds, most commonly sulfuric and nitric acid. These acidic compounds then either mix with natural precipitation and fall to the earth as acid rain, or remain dry and then settle to the ground. In the U.S., coal-fired power plants are the single largest source of SO_2 pollution (66%) and the second largest source of NO_x pollution.

Acid rain destroys ecosystems, including streams and lakes, by changing their delicate pH balance making them unable to support life. Acid rain can destroy forests, devastate plant and animal life, and eat away at man-made monuments and buildings to effectively destroy our natural and historical treasures.

6.4 Air toxics and mercury

Coal-fired power plants are the largest single man-made source of mercury pollution in the U.S. as well as the world, and are the largest contributor of hazardous air pollutants. In smokestack tests, coal-fired power plants were found to release many air toxics, many of which are known or suspected carcinogens and neurotoxins that can cause development problems, respiratory problems, and aggravate asthma.

Of these air toxics, one of the most dangerous is mercury. Mercury from coal-fired power plants is released into the air through the exhaust system when coal is burned. The primary exposure for Americans occurs when this mercury falls to the earth and runs into our lakes, rivers, and streams and contaminates the fish. Humans can be contaminated when they eat these fish and shellfish. In 2004, 47 states and territories had fish consumption advisories for mercury for at least some of their waters.

Mercury is a developmental toxin, primarily affecting fetal development. In unborn children, it can cause brain damage, mental retardation, blindness, and many other problems. Infants are also exposed to these dangers through contaminated breast milk. While the dangers of mercury are most often associated with women and children, eating fish high in mercury has also been found to put middle-aged men at a greater risk for coronary heart disease.

6.5 Global warming

Burning fossil fuels such as coal releases carbon dioxide (CO_2) pollution, making energy use the single largest source of greenhouse gases in the U.S. and the world. Currently there is 30% more CO_2 in the atmosphere than there was at the start of the Industrial Revolution, and we are well on the way to doubling CO_2 levels in the atmosphere during this century. Although the US has only four percent of the world's population it emits about 25% of global warming pollution.

Power plants emit 40% of total U.S. carbon dioxide pollution, the primary global warming pollutant. Although coal-fired power plants account for just over half of the electricity produced in the U.S. each year, they have been responsible for over 83% of the CO_2 pollution since 1990. Coal-fired power plants have the highest output rate of CO_2 per unit of electricity among all fossil fuels.

The atmospheric concentrations of CO_2 and other greenhouse gases reached a new high in the 1990s, the hottest decade on record. Average global temperatures have risen already by one degree Fahrenheit, and projections indicate an increase of two to ten degrees within this century. The Intergovernmental Panel on Climate Change (IPCC) has reported that global warming threatens human populations and the world's ecosystems with worsening heat waves, floods, drought, extreme weather, and by spreading infectious diseases. Unfortunately, global warming problems continue to grow as more greenhouse gases are spewed into our atmosphere.

Appendix C

General properties and hazard impacts of 27 air pollutants

This section contains two tables. The first one illustrates information on general properties of 27 selected air pollutants emitted from a typical coal-fired power plant. The second table shows brief information about the human health effects and environmental effects of 27 selected air pollutants from coal combustion. These tables are shown below.

Appendix Table C1 General properties of 27 selected air pollutants from coal combustion

Pollutant	Chemical Formula	Molecular Weight (g/mol)	Melting Point (°C)	Boiling Point (°C)	Density (g/cm^3)	CAS Number
Ammonia	NH_3	17.0306	-77.7	-33.34	0.6942 (g/l)	7664-41-7
Antimony	Sb	121.76	631	1750	6.697	7440-36-0
Arsenic	As	74.9216	817	613	5.727	7440-38-2
Barium	Ba	137.327	727	1897	3.51	7440-39-3
Benzene	C_6H_6	78.1121	5.5	80.1	0.8786	71-43-2
Benzo(a)-pyrene	$C_{20}H_{12}$	252.31	179	495	1.4	50-32-8
Beryllium	Be	9.012182	1287	2469	1.85	7440-41-7
Carbon Tetra-chloride	CCl_4	153.82	-22.92	76.72	1.5842	56-23-5
Cadmium	Cd	112.411	321.07	767	8.65	7440-43-9
Chloroform	$CHCl_3$	119.4	-63.5	61.2	1.48	67-66-3

Appendix Table C1 (Continued)

Pollutant	**Chemical Formula**	**Molecular Weight (g/mol)**	**Melting Point (°C)**	**Boiling Point (°C)**	**Density (g/cm^3)**	**CAS Number**
Carbon Monoxide	CO	28.0101	-205.05	-191.5	1.145 (g/l)	638-08-0
Cobalt	Co	58.933195	1768	2927	8.9	7440-48-4
Copper	Cu	63.546	1083	2595	8.96	7440-50-8
Chromium	Cr	51.9961	1907	2672	7.19	7440-47-3
2,3,7,8-TCDD	$C_{12}H_4Cl_4O_2$	322	305-306	-	1.8	1746-01-6
Hydrogen Chloride	HCl	36.4606	-114.24	-85.06	1.00045 (g/l)	7647-01-0
Lead	Pb	207.2	327.43	1749	11.34	7439-92-1
Manganese	Mn	54.938045	1246	2061	7.21	7439-96-5
Mercury	Hg	200.59	-38.83	356.73	13.534	7439-97-6
Naphthalene	$C_{10}H_8$	128.17052	80.2	218	1.16	91-20-3
Nickel	Ni	58.6934	1455	2913	8.908	7440-02-0
Nitrogen Dioxide	NO_2	46.0055	-11.2	21.1	3.4 (kg/m^3)	10102-44-0

Appendix Table C1 (Continued)

Particulate Matter less than 10 microns	PM_{10}	128.17052	80.2	218	1.16	91-20-3
Selenium	Se	78.96	221	685	4.8	7782-49-2
Sulfur Dioxide	SO_2	64.054	-72.4	-10.06	2.551 (g/l)	7446-09-5
Vinyl Chloride	CH_2CHCl	62.498	-153.8	-13.4	0.91 (g/ml)	75-01-4
Xylene	C_8H_{10}	106.16	-47.4	138.5	0.864 (g/ml)	1330-20-7

Source: ATSDR (2005); CMTI (2007); NPI (2007)

Appendix Table C2 Hazard effects of 27 selected pollutants from coal combustion

Air Pollutant	Human Health Effects		Environmental Effects
	Acute	Chronic	
Ammonia	• Swallowing concentrated solutions of ammonia can cause burns in your mouth, throat, and stomach. • Splashing ammonia into your eyes can cause burns and even blindness.	• Exposure to high levels of ammonia in air may be irritating to your skin, eyes, throat, and lungs and cause coughing and burns. • Lung damage and death may occur after exposure to very high concentrations of ammonia.	• Excessive discharges of ammonia may cause oxygen depletion in the receiving body due to eutophication which may be detrimental to many types of aquatic life.
Antimony	• Skin and eye contact can cause irritation and an itchy skin rash • Exposure to antimony can irritate the nose, mouth, throat and lungs causing coughing, wheezing and/or shortness of breath	• **Probable carcinogen in human** • Long-term exposure to antimony may decrease fertility in males and females	• Antimony can be found in soils, waters and air in very small amounts. Antimony will mainly pollute soils.

Appendix Table C2 (Continued)

Air Pollutant	Human Health Effects		Environmental Effects
	Acute	**Chronic**	
Antimony (Continued)	• Acute effect of exposure to antimony also includes headaches, vomiting, nausea, abdominal pain and loss of sleep.	• Repeated exposure can affects the lungs and cause an abnormal chest x-ray to develop • Chronic effects of exposure to antimony may include damage to kidneys, liver and heart, repeated contact can cause ulcers or sores in the nose	• Relatively high levels of antimony may kill small animals. Rats may experience lung, heart, liver and kidney damage prior to death. • Animals that breathe in low levels of antimony for a long time may experience eye irritation and hair loss. • Dogs may experience heart problems even when they are exposed to low levels of antimony

Appendix Table C2 (Continued)

Air Pollutant	Human Health Effects		Environmental Effects
	Acute	Chronic	
Arsenic	• Skin contact can cause irritation, burning, itching and a rash. • Eye contact can cause irritation, and burns. • Breathing arsenic also can irritate the nose and throat • High exposure can contribute to poor appetite, nausea, vomiting and muscle cramps.	• **Known human carcinogen of high potency**. • Long term Inhalation causes lung cancer and even hole in the" bone" dividing the inner nose. • Long term ingestion causes lung, skin, bladder and liver cancer as well as stomach problem. The kidney is affected following chronic inhalation and oral exposure. • Repeated exposure also contributes to burning, numbness and weakness of arms and legs.	• Plants absorb arsenic fairly easily, so that high-ranking concentrations may be present in food. • Decomposed in their bodies.

Appendix Table C2 (Continued)

Air Pollutant	Human Health Effects		Environmental Effects
	Acute	**Chronic**	
Barium	• Skin contact can irritate and burn the skin and eyes. • Breathing Barium can irritate the nose, throat and lungs causing coughing, wheezing and/or shortness of breath.	• Repeated exposure may cause bronchitis to develop with cough, phlegm, and/or shortness of breath. • Barium may damage the kidneys. • Repeated exposure can cause an abnormal chest x-ray.	• Some barium compounds that are released during industrial processes dissolve easily in water and are found in lakes, rivers, and streams.
Benzene	• Breathing very high levels of benzene can result in death, while high levels can cause drowsiness, dizziness, rapid heart rate, headaches, tremors, confusion, and unconsciousness.	• **Known human carcinogen of medium potency.**	

Appendix Table C2 (Continued)

Air Pollutant	Human Health Effects		Environmental Effects
	Acute	Chronic	
Benzene (Continued)	• Eating or drinking foods containing high levels of benzene can cause vomiting, irritation of the stomach, dizziness, sleepiness, convulsions, rapid heart rate, and death.	• The major effect of benzene from long-term exposure is on the blood. Benzene causes harmful effects on the bone marrow and can cause a decrease in red blood cells leading to anemia. • It can also cause excessive bleeding and can affect the immune system, increasing the chance for infection. • Some women who breathed high levels of benzene for many months had irregular menstrual periods.	• Benzene can pass into the air from water and soil. It reacts with other chemicals in the air and breaks down within a few days but in water or soil it tends not to break down contaminating soil or water. Fortunately, it does not build up in plant and animals.

Appendix Table C2 (Continued)

Air Pollutant	**Human Health Effects**		**Environmental Effects**
	Acute	**Chronic**	
Benzo(a)-pyrene	• Exposure to either low or high level of benzo(a)pyrene causes skin irritation with rash or burning sensation, color changes formation of warts.	• **Probable human carcinogen** • Repeated exposure to benzo(a)pyrene may cause bone marrow toxicity and heritable genetic damage to human germ cells.	• The substance is very toxic to aquatic organisms. • Bioaccumulation of this chemical may occur in fish, in plants and in molluscs. • The substance may cause long-term effects in the aquatic environment.
Beryllium	• The most commonly known effect of beryllium is called berylliosis, a dangerous and persistent lung disorder that can also damage other organs, such as the heart.	• **Known carcinogen in human**	• Beryllium exists in air as very small dust particles and usually settles in sediment. Beryllium is not likely to move deeper into the soil and dissolve within groundwater.

Appendix Table C2 (Continued)

Air Pollutant	**Human Health Effects**		**Environmental Effects**
	Acute	**Chronic**	
Beryllium (Continued)	• Exposure to beryllium can also cause allergic reactions with people that are hypersensitive to this chemical.	• Long time exposure to beryllium may contribute to development of an inflammatory reaction in the respiratory system called chronic beryllium disease (CBD), which not only makes people feel weak and tired, but also causes difficulty in breathing. It can also result in anorexia, weight loss.	• In water, chemicals will react with beryllium, causing it to become insoluble which is positive because the water-insoluble form of beryllium can cause much less harm to organisms than the water-soluble form. • Some fruits and vegetables such as kidney beans and pears may contain significant levels of beryllium. These levels can enter animals that eat them, but luckily most animals excrete beryllium quickly through urine and feces.

Appendix Table C2 (Continued)

Air Pollutant	**Human Health Effects**		**Environmental Effects**
	Acute	**Chronic**	
Carbon Tetra-chloride	• Exposure to beryllium can also cause allergic reactions with people that are hypersensitive to this chemical. • High exposure to carbon tetrachloride can cause liver, kidney, and central nervous system damage. These effects can occur after ingestion or breathing carbon tetrachloride. • The liver is especially sensitive to carbon tetrachloride because it enlarges and cells are damaged or destroyed. Kidneys also are damaged.	• **Probable carcinogen in human** • If exposure lasts long, the nervous system, including the brain, is affected. People may feel intoxicated and experience headaches, dizziness, sleepiness, and nausea and vomiting. These effects may subside if exposure is stopped, but in severe cases, coma and even death may occur.	• Carbon tetrachloride moves very quickly into the air upon release, so most of it is in the air. It can be broken down or transformed in soil and water within several days. • When it does break down, it forms chemicals that can destroy ozone in the upper atmosphere.

Appendix Table C2 (Continued)

Air Pollutant	Human Health Effects		Environmental Effects
	Acute	Chronic	
Carbon Tetra-chloride	• Exposure to beryllium can also cause allergic reactions with people that are hypersensitive to this chemical. • High exposure to carbon tetrachloride can cause liver, kidney, and central nervous system damage. These effects can occur after ingestion or breathing carbon tetrachloride. • The liver is especially sensitive to carbon tetrachloride because it enlarges and cells are damaged	• **Probable carcinogen in human** • If exposure lasts long, the nervous system, including the brain, is affected. People may feel intoxicated and experience headaches, dizziness, sleepiness, and nausea and vomiting. These effects may subside if exposure is stopped, but in severe cases, coma and even death may occur.	• Carbon tetrachloride moves very quickly into the air upon release, so most of it is in the air. It can be broken down or transformed in soil and water within several days. • When it does break down, it forms chemicals that can destroy ozone in the upper atmosphere.

Appendix Table C2 (Continued)

Air Pollutant	Human Health Effects		Environmental Effects
	Acute	Chronic	
Cadmium	• High exposure to Cadmium may cause nausea, salivation, vomiting, abdominal cramps and diarrhea. • Breathing Cadmium can irritate the lungs causing coughing and/or shortness of breath. • Higher exposures can cause a build-up of fluid in the lungs (pulmonary edema), a medical emergency, with severe shortness of breath.	• **Known carcinogen in human** • Kidney and liver damage, and lung disorder occur as a result of chronic inhalation and oral exposure to cadmium. • Reproductive problem is another effect of long term exposure to cadmium. • Repeated exposure may cause bronchitis to develop with cough, phlegm, and/or shortness of breath. •	• Cadmium strongly adsorbs to organic matter in soils. When cadmium is present in soils it can be extremely dangerous, as the uptake through food will increase. Soils that are acidified enhance the cadmium uptake by plants. This is a potential danger to the animals that are dependent upon the plants for survival.

Appendix Table C2 (Continued)

Air Pollutant	**Human Health Effects**		**Environmental Effects**
	Acute	**Chronic**	
Cadmium (Continued)			• They can die at very low concentrations and this has consequences for the soil structure. When cadmium concentrations in soils are high they can influence soil processes of microrganisms and threat the whole soil ecosystem.
Chloroform	• Breathing about 900 parts of chloroform per million parts air (900 ppm) for a short time can cause dizziness, fatigue, and headache.	• **Probable carcinogen in human** • Breathing air, eating food, or drinking water containing high levels of chloroform for long periods of time may damage your liver.	• Chloroform evaporates easily into the air. Most of the chloroform in air breaks down eventually, but it is a slow process. The breakdown products in air include phosgene and hydrogen chloride.

Appendix Table C2 (Continued)

Air Pollutant	Human Health Effects		Environmental Effects
	Acute	Chronic	
Carbon Monoxide (Continued)	• Breathing carbon monoxide can cause headache, dizziness, fatigue, nausea and lightheadedness. • Higher exposure to carbon monoxide can cause sleepiness, hallucinations, convulsions and loss of consciousness • High level exposure to carbon monoxide can contribute to memory and personality changes, mental confusion and loss of vision.	• Reproductive problem could be one of the results of repeated breathing carbon monoxide • Inhaling carbon monoxide for a long time can result in damage to heart and nervous system.	• It mainly contributes to photochemical smog with visual degradation.

Appendix Table C2 (Continued)

Air Pollutant	Human Health Effects		Environmental Effects
	Acute	Chronic	
Cobalt	- Exposure to cobalt dust can irritate the skin, eyes, note and throat	- **Probable carcinogen in human** - Exposure to cobalt may damage male reproductive system and may also cause a skin allergy resulting in itching and a skin rash - Chronic health effect of long term exposure to cobalt includes asthma, shortness of breath, cough, chest tightness as well as damage to kidneys, heart, liver and thyroid - Repeated exposure to cobalt dust can cause scarring of the lungs.	- Cobalt cannot be destroyed once it has entered the environment. It may react with other particles or adsorb on soil particles or water sediment mostly ending up in soils and sediments. - Soils that contain very low amounts of cobalt may grow plants that have a deficiency of cobalt. When animals graze on these grounds they suffer from lack of cobalt, which is essential for them.

Appendix Table C2 (Continued)

Air Pollutant	Human Health Effects		Environmental Effects
	Acute	Chronic	
Copper	• Exposure to copper dust and fume can irritate the eyes, nose and throat causing coughing, wheezing and nosebleeds. • Copper fume may cause "metal fume fever." This is a flu like illness with symptoms of metallic taste, fever and chills, aches, chest tightness and cough. The symptoms may be delayed for several hours after exposure and usually last a day or two.	• Long term exposure to copper may decrease fertility in males and females. • Repeated exposure can cause chronic irritation of the nose and may cause ulcers and a hole in the "bone" dividing the inner nose. • Copper may also cause a skin allergy. If allergy develops, very low future exposure can cause itching and a skin rash.	• Copper does not break down in the environment and because of that it can accumulate in plants and animals when it is found in soils. On copper-rich soils only a limited number of plants have a chance of survival. That is why there is not much plant diversity near copper-disposing factories. Due to the effects upon plants copper is a serious threat to the productions of farmlands.

Appendix Table C2 (Continued)

Air Pollutant	Human Health Effects		Environmental Effects
	Acute	Chronic	
Copper (Continued)			• Copper can interrupt the activity in soils, as it negatively influences the activity of microrganisms and earthworms. The decomposition of organic matter may seriously slow down because of this.
Chromium	• High exposure to chromium VI may result in renal toxicity, gastrointestinal hemorrhage and internal hemorrhage.	• **Known human carcinogen of high potency**. • Chronic effects from chromium exposure are inflammation of the respiratory tract, effects in the kidneys, liver and gastrointestinal tract.	• Plants usually absorb only chromium (III) which is an essential element for organisms that can disrupt the sugar metabolism and cause heart conditions.

Appendix Table C2 (Continued)

Air Pollutant	**Human Health Effects**		**Environmental Effects**
	Acute	**Chronic**	
Chromium (Continued)		• Breathing Chromium for a long has been reported to cause lung allergy. Once allergy develops, even small future exposure may cause coughing, wheezing, or shortness of breath.	• High concentrations of chromium, due to the disposal of metal products in surface waters, can damage the gills of fish.
2,3,7,8-Tetrachloro-dibenzo-p-dioxin	• The acute effect is Chloracne resulting from the accidents or significant contamination events. It is basically a severe skin disease with acne-like lesions that occur mainly on the face and upper body.	• **Known human carcinogen of medium potency**. • It also contributes to reproductive and developmental problem, together with immune system problem.	• When entering the bodies of animals, it accumulates through food chain increasing the risk of lung cancer. • Dioxin can cause a variety of effects in animals, such as weight loss, liver damage, and disruption of the endocrine system.

Appendix Table C2 (Continued)

Air Pollutant	Human Health Effects		Environmental Effects
	Acute	Chronic	
2,3,7,8-Tetrachloro-dibenzo-p-dioxin (Continued)		• Long term exposure to high concentrations of dioxin may induce long term alterations in glucose metabolism and subtle changes in hormonal levels of people.	• It also causes reproductive damage and birth defects.
Hydrogen Chloride	• Exposure to hydrogen chloride can severely irritate and burn the skin and eyes with possible eye damage and loss of sight. • Breathing hydrogen chloride can irritate the nose and throat.	• Long term exposure to hydrogen chloride may cause yellowing and erosion of the teeth. • Repeated exposures may cause bronchitis to develop with cough, phlegm, and/or shortness of breath.	• Hydrogen chloride can dissociates readily in water to chloride and hydronium ions (an ion is an electrically charged atom or molecule), which ultimately lowers the pH of the water (makes it more acidic), called acidification.

Appendix Table C2 (Continued)

Air Pollutant	**Human Health Effects**		**Environmental Effects**
	Acute	**Chronic**	
Hydrogen Chloride (Continued)	• Higher exposures can cause a build-up of fluid in the lungs (pulmonary edema), a medical emergency, with severe shortness of breath.	• Repeated exposure to extremely high level of hydrogen chloride can even cause swelling and spasm of the throat and suffocation, and even death. • Some people may develop an inflammatory reaction to hydrogen chloride.	
Lead	• Lead can irritate the eyes on contact. • Breathing Lead can irritate the nose and throat.	• **Lead is also considered as probable carcinogenic to humans.** • Repeated exposure to lead can result in poisoning symptoms, such as metallic taste.	• Lead accumulates in the bodies of water organisms and soil organisms. These will experience health effects from lead poisoning.

Appendix Table C2 (Continued)

Air Pollutant	Human Health Effects		Environmental Effects
	Acute	Chronic	
Lead (Continued)	• Other health effects such as a metallic taste in the mouth, vomiting and constipation or bloody diarrhea might also be expected to occur after exposure to lead.	• High or repeated exposure may damage the nerves causing weakness, "pins and needles," and poor coordination in the arms and legs. • Long-term exposure to high levels of lead can cause muscle and joint pains and weakness.	• Health effects on shellfish can take place even when only very small concentrations of lead are present. Body functions of phytoplankton can be disturbed when lead interferes. • Phytoplankton is an important source of oxygen production in seas and many larger sea-animals eat it.
Manganese	• Breathing Manganese can irritate the nose, throat and lungs causing coughing, wheezing and/or shortness of breath.	• Long term exposure to manganese may damage male reproductive system and may decrease fertility in males.	• In plants, manganese ions are transported to the leaves after uptake from soils.

Appendix Table C2 (Continued)

Air Pollutant	**Human Health Effects**		**Environmental Effects**
	Acute	**Chronic**	
Manganese (Continued)	• Exposure to Manganese can cause “metal fume fever.” This is a flu-like illness with symptoms of metallic taste in the mouth, headache, fever and chills, aches, chest tightness and cough. The symptoms may be delayed for several hours after exposure and usually last for a day or two.	• Early symptoms after being exposed to manganese include poor appetite, weakness and sleepiness. Later effects include changes in speech, balance, mood and personality, loss of facial expressions, poor muscle coordination and muscle cramps. • Other chronic health effects of exposure to manganese include permanent lung, liver and brain damage	• When too little manganese can be absorbed from the soil, this causes disturbances in plant mechanisms. For instance disturbance of the division of water to hydrogen and oxygen, in which manganese plays an important part. • Manganese can cause both toxicity and deficiency symptoms in plants. When the pH of the soil is low manganese deficiencies are more common.

Appendix Table C2 (Continued)

Air Pollutant	**Human Health Effects**		**Environmental Effects**
	Acute	**Chronic**	
Mercury	• Inhalation exposure to mercury results in central nervous system effects and effects on gastrointestinal tract and respiratory system. • Other effects include chest pain, shortness of breath, eye irritation and nose irritation. • Eye and skin contact with mercury lead to eye and skin irritation. • Exposure to high levels of mercury can irritate the nose, throat and lungs.	• Major effect from chronic exposure to mercury is kidney damage, developmental effects and reproductive problem. • Mercury may cause a skin allergy. If allergy develops, very low future exposure can cause itching and a skin rash. • Repeated contact (usually more than five years) may cause clouding of the eyes and a gray color to the skin.	• Once mercury has reached surface waters or soils microorganisms can convert it to methyl mercury, a substance that can be absorbed quickly by most organisms and is known to cause nerve damage. • Fish are organisms that absorb great amounts of methyl mercury from surface waters every day. As a consequence, methyl mercury can accumulate in fish and in the food chains that they are part of.

Appendix Table C2 (Continued)

Air Pollutant	Human Health Effects		Environmental Effects
	Acute	Chronic	
Mercury (Continued)		• Symptoms include tremors (shaking), trouble remembering and concentrating, gum problems, increased salivation, loss of appetite and weight, and changes in mood and personality. These can be severe and cause hallucinating and psychosis.	
Naphthalene	• Exposure to high level of naphthalene by ingestion may result in death. • Exposure to large amounts of naphthalene may also damage.	• **Probable human carcinogen** • Long term exposure to naphthalene cause changes in the liver and harmful effects on the kidneys, heart, lungs and nervous system.	• Naphthalene can dissolve in water and may be present in drinking water from wells close to landfills.

Appendix Table C2 (Continued)

Air Pollutant	**Human Health Effects**		**Environmental Effects**
	Acute	**Chronic**	
Naphthalene (Continued)	• Other acute effects include nausea, vomiting, diarrhea, blood in the urine, and a yellow color to the skin.		• Therefore, when it is released into aquatic ecosystems, it may cause long term effects in the aquatic environment and change the entire ecosystem as a whole.
Nickel	• Nickel can irritate the eyes and skin	• **Probable carcinogen in human (lung, nose, larynx and prostate cancer)** • Exposure to nickel may cause a skin allergy. If allergy develops, very low future exposure can cause itching and a rash. • Nickel may cause an asthma-like allergy.	• There is not much information available on the effects of nickel upon organisms, but high nickel concentrations on sandy soils can clearly damage plants and high nickel concentrations in surface waters can diminish the growth rates of algae.

Appendix Table C2 (Continued)

Air Pollutant	Human Health Effects		Environmental Effects
	Acute	Chronic	
Nickel (Continued)		• Breathing Nickel can cause a sore or hole in the "bone" (septum) dividing the inner nose. • Health effects of repeated exposure to nickel include not only damage to kidneys, liver, and lungs function but also heart disorder.	• For animals, nickel is an essential foodstuff in small amounts but nickel is not only favorable as an essential element; it can also be dangerous when the maximum tolerable amounts are exceeded. This can cause various kinds of cancer on different sites within the bodies of animals.
Nitrogen Dioxide	• Dermal contact can irritate and burn the skin and eyes with possible eye damage.	• Repeated exposure to levels of nitrogen dioxide increases susceptibility to respiratory illnesses.	• The reaction of nitrogen dioxide with chemicals produced by sunlight leads to the formation of nitric acid.

Appendix Table C2 (Continued)

Air Pollutant	**Human Health Effects**		**Environmental Effects**
	Acute	**Chronic**	
Nitrogen Dioxide (Continued)	• Higher exposures can cause a build-up of fluid in the lungs (pulmonary edema), a medical emergency, with severe shortness of breath. • High levels can interfere with the ability of the blood to carry oxygen causing headache, fatigue, dizziness, and a blue color to the skin and lips.		• Ozone is associated with asthma, reduced lung function, adverse birth outcomes and allergen sensitization
Particulate Matter less than 10 microns	• Exposure to PM_{10} may cause breathing difficulties due to damage and irritation of the lungs.	• Chronic effects of particulate matter are asthma attack, heart rate variability, and heart attacks.	• Particle pollution can stain and damage stone and other materials.

Appendix Table C2 (Continued)

Air Pollutant	**Human Health Effects**		**Environmental Effects**
	Acute	**Chronic**	
Particulate Matter less than 10 microns (Continued)	• Eye, nose and skin irritation also occur as a result of exposure to PM_{10}.		• It is the largest single contributor to uncertainties in predicting anthropogenic climate change. • Particles can be carried over long distances by wind and then settle on ground or water. The effects of this settling include: making lakes and streams acidic; changing the nutrient balance in coastal waters and large river basins; depleting the nutrients in soil; damaging sensitive forests and farm crops.

Appendix Table C2 (Continued)

Air Pollutant	Human Health Effects		Environmental Effects
	Acute	Chronic	
Selenium	• Exposure to selenium can irritate and burn the skin and eyes • Breathing selenium can irritate the nose, throat and lungs causing coughing and shortness of breath • Nausea, vomiting, diarrhea, abdominal pain and headache are acute results of exposure to selenium	• Repeated exposure to selenium contribute to skin rash as well as a garlic odor on the breath, metallic taste, irritability, fatigue, loss of nails and hair and depression • Extremely overexposure to selenium for long time may result in death	• There is evidence selenium can accumulate in the body tissues of organisms and can than be passed up through the food chain. Usually this bio-magnification of selenium starts when animals eat a lot of plants that have been absorbing large amounts of selenium, prior to digestion.
Sulfur Dioxide	• Contact can irritate and burn the skin and eyes with possible eye damage.	• Long term exposure to sulfur dioxide may decrease fertility in males and females.	• Haze occurs when light is scattered or absorbed by particles and gases in the air.

Appendix Table C2 (Continued)

Air Pollutant	Human Health Effects		Environmental Effects
	Acute	**Chronic**	
Sulfur Dioxide (Continued)	• Breathing sulfur dioxide can irritate the nose and throat. • Breathing sulfur dioxide can irritate the lungs causing coughing and/or shortness of breath. • Higher exposures can cause a build-up of fluid in the lungs (pulmonary edema), a medical emergency, with severe shortness of breath.	• Repeated exposure can cause loss of sense of smell, headache, nausea and dizziness. • Inhalation of sulfur dioxide can irritate the lungs and repeated inhalation may cause bronchitis to develop with cough, phlegm, and/or shortness of breath. • Long term inhalation of sulfur dioxide also cause heart and lung diseases.	• Sulfate particles are the major cause of reduced visibility in many countries. • It also contributes to London smog. • SO_2 and nitrogen oxides react with other substances in the air to form acids, which fall to earth as rain, fog, snow, or dry particles. Some may be carried by the wind for hundreds of miles. • Acid rain damages forests and crops, changes the makeup of soil.

Appendix Table C2 (Continued)

Air Pollutant	**Human Health Effects**		**Environmental Effects**
	Acute	**Chronic**	
Sulfur Dioxide (Continued)			• SO_2 accelerates the decay of building materials and paints, including irreplaceable monuments, statues, and sculptures that are part of our nation's cultural heritage.
Vinyl Chloride	• Breathing high levels of vinyl chloride can cause dizziness or sleepiness • Breathing very high levels can cause people to pass out, and breathing extremely high levels can even cause death.	• Known human carcinogen of medium potency. • Some people who have breathed vinyl chloride for several years have changes in the structure of their livers.	• Vinyl chloride in water or soil evaporates rapidly if it is near the surface. Vinyl chloride in the air breaks down in a few days to other substances, some of which can be harmful.

Appendix Table C2 (Continued)

Air Pollutant	Human Health Effects		Environmental Effects
	Acute	Chronic	
Xylene	• High levels of exposure for short periods can cause headaches, lack of muscle coordination, dizziness, confusion, and changes in one's sense of balance. • Exposure of people to high levels of xylene for short periods can also cause irritation of the skin, eyes, nose, and throat; difficulty in breathing; problems with the lungs; delayed reaction time; memory difficulties.	• Inhalation of xylene vapors can also result in neurologic symptoms similar to alcohol intoxication. • Gastrointestinal symptoms of nausea, vomiting, and gastrointestinal discomfort have been noted in workers exposed to xylene vapors for a long time.	• Xylene builds up in fish, shellfish, plants, and other animals living in xylene-contaminated water which causes adverse effects on human who consume these plant or animals.

Source: Howard (1988); Harold (1998); Wright and Welbourn (2002); ATSDR (2005); CMTI (2007); NPI (2007)

Appendix D

Three hazard rankings for 27 air pollutants

This section contains detailed information on three hazards ranking systems mentioned within this study earlier. These systems include NPI ranking, IRCH ranking and CERCLA ranking.

1. NPI Ranking

It is the ranking of toxic pollutants/substances by National Pollution Inventory (NPI) under Australian Government. Approximately 90 substances were considered for inclusion on the NPI reporting list. A ranking and total hazard score was given based on health and environmental hazards to the substance.

1.1 Hazard scores and ranking of substances

Initially, around 400 substances were drawn up in the list. Excluded from the list were substances banned in Australia or scheduled for phase-out, and those substances for which other reporting was in place because of their ozone depleting or greenhouse effects. Although the scoring system could be used for agricultural and veterinary chemicals as well as industrial chemicals, the treatment was not felt to be ideal and so agvets were also excluded. They may offer an opportunity to do this.

Each substance on the list was evaluated on 0-3 scales for human health effects, environmental effects, and exposure. The health and environmental effects were summed to give 0-6 hazard score, and this was multiplied by the exposure score so as to give a total risk score on a 0-18 scale which facilitated ranking of this substances.

Risk = Hazard (Hunan Health + Environment) x Exposure

Recommendations were made on the way this ranking could be used to generate the reporting list.

Each of the three contributions to the risk score was itself constructed by assigning scored (0-3) to a range of attributes, and these components were combined as follows:

1.1.1 Human health effects

Evaluating acute toxicity, chronic toxicity, carcinogenicity, and reproductive toxicity of a given substance to arrive at a score on its effect on human health.

Human Health = (Acute Toxicity + Chronic Toxicity)/2

Chronic human health toxicity is calculated as a function of:

(Chronic + Reproductive Toxicity + Carcinogenicity)/3

1) Acute toxicity

The following European Correction (EC) Directive Risk Phases were applied in arriving a score for acute toxicity effects on human health as shown below.

High “3” (Very Toxic) - was assigned if the substance was described by one of the EC Risk Phases R26 to R28 and R35:

R26- Very toxic by inhalation;
R27- Very toxic in contact with skin;
R28- Very toxic if swallowed; or
R35- Causes severe burns

Medium “2” (Toxic) - EC Risk Phrases R23 to R25 and R34:

R23 – Toxic by inhalation;
R24 – Toxic in contact with skin;
R25 – Toxic if swallowed; or
R34 – Causes burns

Low “1” (Harmful) – EC Risk Phrases R20 to R22, R36 to R38 and R65:

R20 – Harmful by inhalation;
R21 – Harmful in contact with skin;
R22 – Harmful if swallowed;
R36 – Irritating to eyes;
R37 – Irritating to respiratory systems;
R38 – Irritating to skin; or
R65 – Harmful if taken in lungs

Zero – Evidence indicating negligible Acute Toxicity; no EC Risk Phrases and no evidence or $LD_{50} \geq 5000$.

2) Chronic toxicity

Just as for acute toxicity, chronic toxicity scores are arrived at by applying EC Risk Phrases.

High “3” (Very Toxic): R39 – Danger of very serious irreversible effects

Medium “2” (Toxic):

R33 – Danger of cumulative effect;
R42 – May cause sensitization by inhalation;
R43 – May cause sensitization by skin contact

Low “1” (Harmful): - Limited evidence or no evidence proving negligible effect

Zero - Sufficient human or animal evidence indicating a lack of developmental toxicity or adequate evidence for negligible chronic effects

3) Reproductive toxicity

Reproductive toxicity is a collector for a range of toxicological effects. Specifically EC Risk Phrases for the following scores have been used.

High “3”

- R60 (category 1) – Known to impair fertility;
- R61 (category 1) – Known to cause harm to the unborn child

Medium “2”

- R60 (category 2) – May impair fertility;
- R61 (category 2) – May cause harm to the unborn child;

Low “1” – EC Risk Phrases R63 and R62:

R64 – May cause harm to breast feeding babies;
R63 – Possible risk of harm to the unborn child;
R62 – possible risk of impaired fertility

Zero – Known, probable or possible negative evidence

4) Carcinogenicity toxicity

Scoring for carcinogenicity is based on consideration of EC Risk Phrases using the categories developed by the international Agency for Research on Cancer (IARC) as a default. In applying risk phrases, sub-categories have been used to provide adequate sensitivity for scoring.

High “3” – EC Risk Phrases R45 (category 1) and R49 (category 1):

R45 (category 1) - May cause cancer
R46 (category 1) - May cause heritable genetic damage
R49 - May cause cancer by inhalation

Medium “2” – EC Risk Phrases R45 (category 2), R49 (category 2) and R46:

R45 (category 2) – May cause cancer
R49 (category 2) – may cause cancer by inhalation
R46 (category 2) – May cause heritable genetic damage

Low “1” – EC Risk Phrases R40 (category 3):

R40 (category 3 or M3) – Possible risk of irreversible effects

Zero - Adequate evidence indicating negligible effects from appropriate animal tests

1.1.2. Environmental effects

Evaluating acute toxicity, chronic toxicity, persistence, and bioaccumulation of a given substance to arrive at a score on its effect on the environment.

Environment = (Acute Toxicity + Chronic Toxicity)/2

The chronic environment component may be derived as a single score or it may need to be arrived at by combination of the three factors described above, and normalization to the 0-3 scale, before it is used in determining the single environment score.

Chronic = (default chronic toxicity + persistence + bioaccumulation)/3

1) Acute toxicity

Acute toxicity was measured by the appropriate risk phrase based on toxicity to aquatic organisms. In general, aquatic organisms are more sensitive to chemical effects than are terrestrial organisms, and it is thus appropriate to use such criteria in the general case. If no information was available from the risk phrases then the default criteria were used.

High “3” (Very Toxic) – EC Risk Phrase R50: Very toxic to aquatic organisms

Medium “2” (Toxic) - EC Risk Phrase R51, R54 and R55:

R51 – Toxic to aquatic organisms;
R24 – Toxic to flora;
R25 – Toxic to fauna

Low “1” (Harmful) – EC Risk Phrase R52: Harmful to aquatic organisms

Zero – Evidence is available indicating negligible effect

2) Combined chronic toxicity, persistence, and bioaccumulation

A range of tests was used to generate a single score for chronic toxicity, persistence and bioaccumulation. In the first instance, the chronic toxicity criteria applied by the EX in risk phrases R53 and R58 incorporate some degree of chronic toxicity, persistence and bioaccumulation, so application of the risk phrase is equivalent to generating a combined score. Thus, chronic toxicity is attributed as follows:

High “3” (Very Toxic): EC Risk Phrases R53 and R58:

R53 – My cause long term adverse effects in the aquatic environment;
R58- May cause long term adverse effects in the environment

If no appropriate risk phrase was assigned, then separate scores for the three components were evaluated as described below.

3) Chronic toxicity

High “3” (Very Toxic)

- Aquatic MATC < 10 ppb;
- Plant EC_{50} < 100 ppb

Medium “2” (Toxic)

- 10 ppb < aquatic MARC < 100 ppb;
- 100 ppb < plant EC_{50} < 1 ppm

Low “1” (Harmful)

- Aquatic MATC > 100 ppb;
- Plant EC_{50} > 1 ppm

Zero – Evidence is available indicating negligible effect.

4) Persistence

Persistence may also be considered separately from chronic toxicity, in which case the score is based on a measure of how long the substance remains in the environment. Note that EC Risk Phrases are not applicable, as the EC considered persistence in the context of other attributes.

High “3”

- Aquatic LC_{50} < 1 ppm plus continuous or repeated (C/R) releases or one-time release with chemical half-life < 14 days;
- Aquatic MATC < 100 ppb plus C/R releases or one-time release with chemical half-life < 4 days

Medium “2”

- 1 ppm < aquatic LC_{50} < 10 ppm plus C/R releases or one-time release with chemical half-life < 14 days;
- 100 ppb < aquatic MATC < 1 ppm plus C/R releases or one-time release with chemical half-life < 4 days

Low “1”

- Aquatic $LC_{50} > 10$ ppm plus continuous or repeated (C/R) releases or one-time release with chemical half-life < 14 days;
- Aquatic MATC > 1 ppm plus C/R releases or one-time release with chemical half-life < 4 days

Zero -Evidence is available indicating negligible persistence in the environment.

5) Bioaccumulation

SEC Risk Phrases are not applicable to bioaccumulation scoring as the EC considers bioaccumulation in the context of other attributes.

High “3”

- Aquatic $LC_{50} < 10$ ppm plus BCF < 1000 or measured log P < 4.35 or estimated log P < 5.5;
- Aquatic MATC < 100 ppb plus BCF < 1000 or measured log P < 4.35 or estimated log P < 5.5

Medium “2”

- 10 ppm < aquatic $LC_{50} < 100$ ppm plus BCF < 1000 or measured log P < 4.35 or estimated log P < 5.5;
- 100 ppb < aquatic MATC < 1 ppm plus BCF < 1000 or measured log P < 4.35 or estimated log P < 5.5

Low “1”

- Aquatic $LC_{50} > 100$ ppm plus $BCF < 1000$ or measured $\log P < 4.35$ or estimated $\log P < 5.5$;
- Aquatic $MATC > 1$ ppm plus $BCF < 1000$ or measured $\log P < 4.35$ or estimated $\log P < 5.5$

Zero – Evidence is available indicating negligible bioaccumulation (NPI, 2007).

2. IRCH Ranking

The Indiana Clean Manufacturing Technology and Safe Materials Institute (CMTI) at Purdue University has developed a hazard evaluation system for chemicals that produces separate rankings for ecological effects and occupational health effects, as well as a total hazard score that integrates both types of hazards. This system, the Indiana Relative Chemical Hazard Ranking System (formerly known as 3P2M), combines information about a chemical's toxicity to humans and ecosystems with information about chemical characteristics that influence the likelihood of exposure to a substance.

2.1 The formula

The combined hazard value allows comparative ranking of hazard among chemicals, but does not measure pollution prevention progress. The IRCHS algorithm measures this multiplying the amount of the chemical used by its hazard value and normalizing the product by units of production. This will allow comparisons among scales of production and across time, providing a method adaptable to all stages of the product life cycle and all sizes of facilities and sectors. The IRCHS group investigated defining materials usage and units of production and concluded that these terms would be best defined according to individual manufacturers’ standards.

To date, hazard values have been assigned to over one thousand chemicals. The hazard values are on CMTI's Website, www.ecn.purdue.edu/CMTI, which averages 500 hits per month. These chemicals are all of the CERCLA chemicals plus any additional chemicals commonly used by the four priority manufacturing sectors. The most recent additions to the list were added the first half of 2001, and were all of the Extremely Hazardous Substances (EHS) identified by OSHA and EPA, all of the Stratospheric Ozone Depleters (SOD) identified by EPA, and the thirty seven High Production Volume (HPV) chemicals designated by EPA for mandatory testing.

The program allows chemical vendors to "advertise their products as less toxic than similar products, if 3P2M verifies this," and is being received "very well by the vendor community, who are aware of it." And for the solvent end user, the program lets them compare the toxicity of similar products, which can be a huge aid in determining which product to use if all else is equal or near equal.

The final measurement method for use by the Institute is:

Total Hazard Value = normalized worker exposure hazard value + normalized environmental hazard value /2 or

$$[(1.15)(\text{HVhlth X HVexp}+2\text{HVsafe})]+[(\text{HVwater}+\text{HVair}+\text{HVland}+\text{HVglobal})/3.5]/2 \text{ or}$$

$$[(1.15)(\{\text{HVchronic}+\text{HVacute}\}\{\text{HVvp}+\text{HVoral}+\text{HVskin}+\text{HVdm}\}+2\{\text{HVflam}+\text{HVreact}+\text{HVcor}\})+(\{\text{HVutn}+\text{HVcrit}+\text{HVhap}+\text{HVhrp}+\text{HVehs}+\text{HVp}+\text{HVu}+\text{HVign}+\text{HVreact}+\text{HVcor}+\text{HVtox}+\text{HVsod}\}/3.5)]/2 \text{ or}$$

$$[(1.15)(\text{Worker Exposure Hazard Value})]+[(\text{Environmental Hazard Value})/3.5]/2.$$

2.2 Environmental hazard value

IRCH environmental hazard value scores indicate how a chemical compares with others in terms of its capacity to impact human health, ecosystems, or environmental health generally. The scores combine the UTN total hazard value scores with air, land, and global hazard values that are based on the presence of a chemical on several regulatory and target lists. The graphic shows where a compound's hazard score falls relative to all chemicals that have been ranked using this system, indicating whether it is more or less hazardous than most chemicals. Chemicals that score at the far right end of the scale are significantly more hazardous (in the worst 10% of all chemicals according to this scoring system).

All chemicals scored by a system have been placed in "bins" defined by percentiles (e.g., a chemical's score is in the least toxic 25% of chemicals scored by a system). The graphic illustrates which bin a chemical falls in according to each scoring system in Scorecard. Looking across these different systems, it is possible to identify chemicals that consistently score as high or low hazards, as well as chemicals that score high on some measures (such as human health hazards) but low on others (such as ecological hazards).

The environmental hazard component consists of four parts: the Water, Air, Land and the Global Hazard Values. The water hazard value will be the University of Tennessees already determined hazard value, while the air hazard value will be the sum of the hazard values assigned if the chemical is:

- A criteria pollutant (HV=20)
- A Hazardous Air Pollutant (HAP) (HV=40)
- A High Risk Pollutant (HRP) (HV=20)
- An Extremely Hazardous Substance (EHS) (HV=20)

The land hazard value will be the hazard value assigned if the chemical is:

- On the Hazardous Waste P List (HV=70)
- On any of the Hazardous Waste F, K, or U Lists (HV=35) (F001 - F005 only; Chemical must be specifically listed on K list)
- Exhibits the Hazardous Waste Characteristic of: Ignitability (HV=15), Reactivity (HV=15), Corrosivity (HV=15), and Toxicity (HV=15).

The global hazard value will be the hazard value assigned if the chemical is a Stratospheric Ozone Depleter (SOD). These values are:

- 50 if the chemical is a Class I SOD
- 25 if the chemical is a Class II SOD

Therefore, accordingly, the components of the environmental hazard value are:

- HVwater = Normalized UTN HV
- HVair = HVcrit.+HVhrp+HVvhap+HVehs
- HVglobal = HVsod
- HVland = HVvp+HVu+HVign+HVreact+HVcor+HVtox

The values for the water, air, and land hazard portions of the algorithm will be normalized to a highest probable score of 100. The value for the global hazard portion will be normalized to a highest probable score of 50. These four parts will be added together and divided by 3.5 (the global hazard value is 1/2 the value of the other three) to determine the environmental hazard value. The final Environmental Hazard algorithm is HVenvhaz = (HVwater+HVair+HVglobal+HVland)/3.5.

2.3 Worker exposure hazard value

IRCH worker exposure hazard scores indicate how a chemical compares with others in terms of its capacity to impact the health of a factory worker. The graphic shows where a compound's hazard score falls relative to all chemicals that have been ranked using this system, indicating whether it is more or less hazardous than most chemicals. Chemicals that score at the far right end of the scale are significantly more hazardous (in the worst 10% of all chemicals according to this scoring system).

All chemicals scored by a system have been placed in "bins" defined by percentiles (e.g., a chemical's score is in the least toxic 25% of chemicals scored by a system). The graphic illustrates which bin a chemical falls in according to each scoring system in Scorecard. Looking across these different systems, it is possible to identify chemicals that consistently score as high or low hazards, as well as chemicals that score high on some measures (such as human health hazards) but low on others (such as ecological hazards).

The worker exposure component will consist of three parts: the Health Effects, the Routes of Exposure, and the Safety Hazard Value. The health effects hazard value will be the sum of the Chronic Hazard Value and the Acute Hazard Value. The chronic hazard value is the more stringent of the toxic or the carcinogenic hazard values. The toxic hazard value (HVtox) is based upon the chemicals Threshold Limit Value (TLV). The hazard values assigned are:

Appendix Table D1 Toxic hazard value based on threshold limit value

TLV (mg/m^3)	**HVtox**
>2500	0.0
≤2500 but >250	1.0
≤250 but >25	2.0
≤25 but >2.5	3.0
≤2.5 but >0.25	4.0
≤0.25	5.0

The carcinogenic hazard value (HVcar) is based upon classifications from EPA ratings and the American Conference of Governmental Industrial Hygienists (ACGIH) ratings. The hazard values assigned are:

Appendix Table D2 Carcinogenic hazard value based on EPA rating

EPA Rating	ACGIH Rating	HVcar
E	A5	0.0
D	A4	0.0
C	N/A	1.5
B2	A3	3.5
B1	A2	4.0
A	A1	5.0

The acute hazard value is the hazard value assigned based upon the Short Term Exposure Limit (STEL) of the chemical. If a STEL exists, the STEL hazard value (HVstel) is 0.5. If a STEL does not exist, the HVstel is 0.0. The routes of exposure hazard value will be the sum of:

- The Vapor Pressure Hazard Value (HVvp)
- The Oral Hazard Value (HVoral)
- The Skin Hazard Value (HVskin)
- The Dust / Mist Hazard Value (HVdm)

The HVvp is based upon the vapor pressure of the chemical at 25° C. The hazard values assigned are:

Appendix Table D3 Vapor pressure hazard value

Vapor Pressure (torr)	**HVvp**
<0.076	0.0
≥0.076 but <0.76	1.0
≥0.76 but <7.6	2.0
≥7.6 but <76	3.0
≥76 but <760	4.0
≥760	5.0

The HVoral is based upon whether or not the chemical can be absorbed through the mouth. Currently, only lead is scored as an oral hazard. If lead is in the chemical compound, the HVoral is 1.0. If lead is not in the chemical compound, the HVoral is 0.0.

The HVskin is based upon whether or not the chemical can be absorbed through the skin. If it can be absorbed as defined by ACGIH, the HVskin is 0.5. If it cannot, the HVskin is 0.0.

The HVdm is based upon the ability of the chemical to produce dusts or mists. Here are the values assigned:

2.3.1 Solids

Condition: Melting Point (MP) > 25ºC, presumed solid at Standard Temperature & Pressure (STP), no note on TLV entry for dust HVdm: 1.5

Condition: TLV entry notes a value for "dust" HVdm: 3.5

Condition: If a chemical may be handled or used both as a solid dust and a sprayed solution of that solid (and neither "dust" or "mist" is present at its

TLV entry), or is used in plating solutions and is capable of creating mist when heated or agitated, then it is given a combined score of: HVdm: 3.0

Condition: If the chemical's MP is close to 25ºC; can exist either as liquid or solid at room temperature HVdm: 2.0

Condition: If a solid is entered in UTN list of compounds (using specific surrogates) only as a solution of soluble solid or characteristically used only as liquid solution HVdm: 1.5

Condition: If a solid tends to be present in airborne smoke particulates resulting from combustion, especially polycyclic aromatic hydrocarbons and chlorinated dibenzo-dioxins and furans HVdm: 1.5

Condition: Friable asbestos, all types HVdm: 5.0

2.3.2 Liquids

Condition: MP < 25ºC, BP > 25ºC, presumably liquid at STP, especially liquid inorganic acids and short-chain fatty acids, especially acetic acid, or alkalis or alkali solutions, presumed capable of creating mist, either when mechanically agitated or splashed or when heated, but no mention in TLV entry of "mist". Includes the gases hydrogen chloride, hydrogen bromide, hydrogen fluoride, hydrogen iodide, ammonia and hydrogen cyanide, which, when dissolved in water, are known respectively as hydrochloric acid, hydrobromic acid, hydrofluoric acid, hydroiodic acid, ammonium hydroxide, and hydrocyanic acid HVdm: 1.5

Condition: TLV entry notes a value for "mist" HVdm: 3.5

Condition: MP > 25ºC, presumed solid at STP. No note on TLV entry for dust, but may be handled, sprayed or used as solution, in characteristic use - usually a pesticide, herbicide or surface spray operation HVdm: 1.5.

2.3.3 Gas

Condition: Boiling point < 25ºC, presumed gas HVdm:0.0

The safety hazard value will be the sum of the flammability hazard value (HVflam), the reactivity hazard value (HVreact) and the corrosivity hazard value (HVcor). The HVflam and HVreact are based upon the flammability of a chemical as defined by the National Fire Protection Association (NFPA). The value is the same as that given by NFPA.

Appendix Table D4 Flammability and reactivity hazard value by NFPA

NFPA	HVflam and HVreact
0	0.0
1	1.0
2	2.0
3	3.0
4	4.0

The HVcor is based upon the corrosivity of the chemical as defined by the U.S. Department of Transportation (DOT). The hazard values are:

Appendix Table D5 Corrosivity hazard value under DOT classification

DOT Classification	HVcor
None	0.0
III	2.0
II	3.0
I	4.0

Therefore, the components of the worker exposure hazard value are:

- HVhealth effects = HVchronic+HVacute
- HVroutes of exposure = HVvp+HVoral+HVskin+HVdm
- HVsafety = HVflam+HVreact+HVcor

The safety hazard value is multiplied by 2 as a weighting factor and the final Worker Exposure algorithm is:

HVwrk exp = (HVhealth)(HVexposure)+2(HVsafety)

3. CERCLA Ranking

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) section 104 (i), as amended by the Superfund Amendments and Reauthorization Act (SARA), requires ATSDR and the EPA to prepare a list, in order of priority, of substances that are most commonly found at facilities on the National Priorities List (NPL) and which are determined to pose the most significant potential threat to human health due to their known or suspected toxicity and potential for human exposure at these NPL sites. CERCLA also requires this list to be revised periodically to reflect additional information on hazardous substances.

This CERCLA priority list is revised and published on a 2-year basis, with a yearly informal review and revision. Each substance on the CERCLA Priority List of Hazardous Substances is a candidate to become the subject of a toxicological profile prepared by ATSDR and subsequently a candidate for the identification of priority data needs. This priority list is based on an algorithm that utilizes the following three components: frequency of occurrence at NPL sites, toxicity, and potential for human exposure to the substances found at NPL sites. This algorithm utilizes data from ATSDR's HazDat database, which contains information from ATSDR's public health assessments and health consultations.

It should be noted that this priority list is not a list of "most toxic" substances, but rather a prioritization of substances based on a combination of their frequency, toxicity, and potential for human exposure at NPL sites. Thus, it is possible for substances with low toxicity but high NPL frequency of occurrence and exposure to be on this priority list. The objective of this priority list is to rank substances across all NPL hazardous waste sites to provide guidance in selecting which substances will be the subject of toxicological profiles prepared by ATSDR.

3.1 Methodology for generating CERCLA priority list

The ranking of hazardous substances on the priority list is based on three criteria, which are combined to result in the total score. The three criteria are:

3.1.1 Frequency of occurrence at NPL sites

ATSDR's HazDat database is the source of data for the frequency of occurrence of substances at NPL hazardous waste sites or facilities. Presence in at least one environmental medium per NPL site constitutes one occurrence.

3.1.2 Toxicity

If available, final Reportable Quantities (RQs) are used to assess the toxicity of candidate substances during the listing activity. If a final RQ is not available, the RQ methodology is applied to candidate substances to establish a Toxicity/Environmental Score (TES). This process is only used in scoring the substances with respect to their toxicity, and does not represent regulatory amounts.

3.1.3 Potential for human exposure

The exposure component is based on two parts: the concentration of the substances in environmental media and the exposure status of populations. HazDat serves as the source of this information. HazDat contains concentration data and exposure information obtained from ATSDR public health assessments and health consultations.

Using these three criteria, the hazard potential of each candidate substance was ranked according to the following algorithm:

Total Score = NPL Frequency + Toxicity + Potential for Human Exposure

(1,800 max. points) (600 points) (600 points) (300 conc. pts.) + (300 exposure pts.)

Substances were ranked on the basis of their total score. Substances considered for the 2005 priority list of hazardous substances came from the universe of substances present at NPL sites, as indicated in HazDat from either health assessment or site file information. Currently, approximately 3,300 uniquely identifiable substances are found at hazardous waste sites according to HazDat. Only those substances found at three or more NPL sites were considered for the priority list; 861 substances were found at three or more sites.

The list of candidate substances was reviewed to identify petroleum-related substances. Substances of petroleum origin are regulated by legislation other than CERCLA and therefore, are excluded from becoming potential toxicological profile candidates under CERCLA. These substances were assigned TES values of zero and total point scores of -1 to place them at the bottom of the list of candidate substances.

3.2 Determination of frequency of occurrence criterion

ATSDR's HazDat database was selected as the source of data for the frequency of occurrence of substances at NPL hazardous waste sites or facilities. The sources of HazDat site-specific information include ATSDR public health assessments and health consultations, and other site-specific documents submitted to ATSDR by EPA, state agencies, and other parties. HazDat has information on approximately 1,674 sites that have been proposed for, listed on, or delisted from the NPL.

HazDat contains information on substances found in various environmental media. The number of NPL sites at which a substance was identified in any environmental medium in health assessment or site-file documents was used to indicate the frequency of occurrence. Contaminants included in HazDat are substances identified in the ATSDR site files as having been positively identified at the site as a result of chemical analyses (i.e., at concentrations above the limits of detection), inventories, or other documentation collected during the ATSDR health assessment process. Substances identified in documents as “Tentatively Identified Compounds” (TICs) are not included in ATSDR's HazDat system and, therefore, were not considered in the determination of frequency-of-occurrence for the priority list. Presence of a substance in at least one environmental medium per NPL site constitutes one occurrence.

The frequency-of-occurrence component of the algorithm was assigned a maximum score of 600 points. These points were distributed between the maximum and minimum frequencies, with the maximum frequency receiving 600 points. Lead had the highest frequency of 1,256 and therefore received 600 frequency points. The assignment of points for the remainder of substances was calculated using the following formula:

$$\frac{\text{Current substance's frequency}}{\text{Maximum frequency}} \times 600$$

For example, if a substance's NPL frequency = 854; then its frequency points = (854/1,256) x 600 = 408.

This method of point assignment was used in an effort to scale the measured frequency values into the allotted point range of 1-600, while maintaining their proportional relationship. Only those substances found at three or more NPL sites were considered for the priority list.

3.3 Determination of toxicity component

The Reportable Quantity (RQ) approach has continued to be used as the toxicity hazard scoring system for several reasons. This approach provides the most complete characterization of toxicity of all hazard scoring systems reviewed; other schemes were more limited in either the consideration of different types of toxic effects, severity of effects, or potency. In addition, toxicity data used in the RQ approach are derived from primary peer-reviewed literature, and RQs have already been established for the majority of substances that are frequently detected at hazardous waste sites. Moreover, the determination of RQ health effect values uses weight-of-evidence considerations in evaluating data.

The reportable quantity ranking scheme was developed by EPA to set RQs for hazardous substances as required by CERCLA. CERCLA requires any person in charge of a vessel or an offshore or onshore facility from which a hazardous substance has been released in a quantity that equals or exceeds its RQ must immediately notify the National Response Center and state and local response authorities of the release. RQs are developed for individual chemicals and for waste streams that have already been designated as hazardous substances under CERCLA.

Each CERCLA hazardous substance is assigned to one of five tiered RQ categories (1, 10, 100, 1,000, and 5,000 pounds) on the basis of acute toxicity, chronic toxicity, carcinogenicity, aquatic toxicity, and ignitability and reactivity. RQs are determined separately for each criterion; the lowest of these is selected as the RQ for the substance, subject to adjustment for potential hydrolysis, photolysis, or biodegradation in the environment. The RQ scoring scheme is described in the following four *Federal Register* notices: 50 FR 13456, April 4, 1985; 51 FR 34534, September 29, 1986; 52 FR 8140, March 16, 1987; 54 FR 35988, August 30, 1989.

The RQ methodology was applied for those candidate substances without final CERCLA RQs in order to establish a Toxicity/Environmental Score (TES). These scores were developed for use only in the ranking methodology and *do not* represent regulatory amounts. TESs have been assigned to more than 450 candidate substances. Substances that received a TES greater than 5,000 (using the RQ methodology) were dropped to the bottom of the candidate list because of their lack of known toxicity and received a rank of #714 and a total score of zero points.

3.3.1 Sources of information used to determine toxicity/environmental score (TES)

Several sources of information on toxicity, reactivity/ignitability, and environmental fate have been used to determine the TESs for substances lacking RQs. In the past and currently, the National Library of Medicine (NLM) online databases are one of the main sources of information. These databases include the Hazardous Substances Data Bank (HSDB), the Registry of Toxic Effects of Chemical Substances (RTECS), Chemical Carcinogenesis Research Information System (CCRIS), Integrated Risk Information System (IRIS), and TOXicology Information OnLINE (Toxline). In addition, EPA's ECOTOXicology database (ECOTOX) is also currently used.

In 1996, the TESs and RQs for the candidate substances was reviewed. For this effort, NLM databases containing toxicity information for the substances were reviewed, along with the AQUIRE database (now part of ECOTOX). The purpose of this review was to determine if any new toxicity information had become available since the substances were first evaluated (most in 1991). As a result, a number of substances had their toxicity values (RQs or TESs) revised to reflect any new information.

3.3.2 Assumptions used in determining toxicity/environmental score

1) Ignitability

Where no specific values were found to express potential for ignitability/reactivity, professional judgement was applied. For example, if a substance was classified as extremely flammable, but no flash point was given, a score of 10 was assigned for the ignitability/reactivity component. Similarly, if no information was found to indicate the substance was ignitable or reactive, the substance was assigned a score of >5,000 for this component of the TES.

2) Aquatic toxicity

Specific aquatic toxicity data were lacking for many substances. In some of these cases, Sax (1984) was used to assess aquatic toxicity. The standard method of reporting aquatic toxicity in this text provides a range of toxicity without identifying the test species. Seventy-five percent of the maximum value was used for the aquatic toxicity component (for example, if the range was 100-1,000, the LC50 value used was 750) for substances that lacked any other source of aquatic toxicity information.

3) Chronic toxicity

Some substances lacked chronic toxicity data in the NLM online databases, but were mentioned in HSDB or Sax as having developmental or reproductive effects at a specified dose. For these substances, the development or reproductive effects were used to assess the chronic toxicity component because these effects are given the highest effect ranking (R_e in the RQ methodology) and potentially occur, regardless of duration of exposure.

4) Carcinogenicity

Substances classified by EPA or the International Agency for Research on Cancer (IARC) in cancer classification groups A, B, or C were assigned TES scores of 1, 10, or 100, respectively. Substances with limited evidence of carcinogenicity in animals, but not classified by IARC or EPA for carcinogenicity, were assigned a TES score of 100. Substances with evidence of carcinogenicity in animals, but noted in the data source as "lacking sufficient evidence for carcinogenicity" by EPA or IARC were not evaluated for carcinogenicity (group D - insufficient evidence). Substances for which no information on carcinogenicity could be located were not evaluated for carcinogenicity.

5) Radionuclides

The RQs for radionuclides are expressed in curies (seven tiered categories), whereas other RQs are expressed in pounds. Before 2001, all radionuclides were assigned a TES of 1 and received the highest number of toxicity points, based on the potential carcinogenicity associated with exposure to various types of radiation. However, in 2001, a reassessment and revision was made to the toxicity scores for radionuclides for purposes of developing this priority list. To provide comparative values and consistency in this activity, the 7 tiered categories of radionuclide RQs (in curies) are now distributed into the toxicity point scale so that the most harmful radionuclides receive the highest number of toxicity points and the less harmful radionuclides receive a lower number of toxicity points. Radionuclides with an RQ equal to 0.001 curie, 0.01 curie, or 0.1 curie still receive a TES of 1 and receive the highest number of 600 points for the toxicity component.

Radionuclides with an RQ equal to 1 curie receive a TES of 10 (400 toxicity points); 10 curies receive a TES of 100 (178 toxicity points); 100 curies receive a TES of 1,000 (53 toxicity points); and 1,000 curies receive a TES of 5,000 (10 toxicity points). This method of point assignment should allow the list to distinguish between the more harmful radionuclides (such as plutonium-238) and less harmful radionuclides (such as krypton-85).

6) Naturally occurring elements

TESs for several of the naturally occurring elements were based on values for the ionized forms of the element rather than the "pure" element because the ionized forms are those most likely to be found in environmental media.

The RQ for phosphorus was not adjusted because of concern in the workgroup that pure phosphorus might in fact be found at certain sites. ATSDR recognizes the uncertainty in assigning TESs to naturally occurring inorganic substances.

Appendix Table D6 Substances with TESs based on ionized forms

CAS Number	Chemical Name	CAS Number	Chemical Name
7439-95-4	Magnesium	7440-09-7	Potassium
7440-23-5	Sodium	7440-24-6	Strontium
7440-46-2	Cesium	7440-67-7	Zirconium
14808-79-8	Sulfate	16887-00-6	Chloride

7) Substances lacking data

For several substances, essentially no relevant information was located. In these cases, TESs were assigned based on the RQs for structurally related substances.

3.3.3 Toxicity component scoring

Various methods to assign points to the TES/RQ values were discussed and evaluated. The assignment of a "log scale" scoring system resulted in overemphasis of those substances that received an RQ or TES of 1 or 10, which overshadowed the other two components of the algorithm (NPL frequency and potential for human exposure) and tended to rank substances solely by their RQ or TES value. A scoring system using a 2/3 cumulative exponential decay was selected as the scoring method for the toxicity component of the priority list. Using this scoring system, the toxicity points value is equal to 2/3 raised to the exponent of the cumulative ordinal rank, multiplied by 600 (the highest value for the toxicity points = 600). The point assignments are presented in the table below.

Appendix Table D7 Toxicity component scoring

Reportable Quantity or Toxicity/Environmental Score	**Ordinal Rank**	**Cumulative Ordinal Rank (COR)**	**2/3 Raised to Exponent of COR**	**Toxicity Points ($2/3^{COR}$ x 600)**
1	0	0	1.0000	600
10	1	1	0.6667	400
100	2	3	0.2963	178
1000	3	6	0.0878	53
5000	4	10	0.0173	10

3.4 Determination of potential for human exposure component

In the approach for the priority list of hazardous substances, the most useful and directly relevant data to assess the potential for human exposure to hazardous substances at NPL sites were identified. The exposure component of the algorithm is based on two factors: concentrations of the substances in environmental media and exposure status of populations as described in ATSDR health assessments or consultations. These two parts of the potential-for-human-exposure portion of the algorithm were assigned a maximum of 300 points each. If no concentration or exposure data were available for the substance, no points were assigned.

3.4.1 Concentrations of substances in environmental media

To provide a means of ranking substances based on concentration data, the following formula for calculating a relative source contribution (SC) was used.

$$SC = \frac{(C_a A_a) + (C_w A_w) + (C_s A_s)}{\text{RQ or TES}}$$

Where C_x = geometric mean of maximum concentration of the substance in a particular environmental medium (a = air, w = water, s = soil); A_x = standard exposure assumption for the particular environmental medium to approximate a theoretical daily dose to humans; and RQ or TES = the Repiortable Quantity or Toxicity/Environmental Score for the substance.

The calculation of the source contribution was included in the methodology to distinguish between those substances that occur at low concentrations but are highly toxic and those substances that occur at higher concentrations but are relatively less toxic.

It is noted that because of the complexity and uncertainty associated with calculating a daily dose for radioactive substances and asbestos compounds, source contribution values were not calculated for these substances.

1) Source of concentration data

HazDat served as the source of concentration data for NPL site contaminants. HazDat contains concentration data for hazardous substances that are documented in ATSDR health assessments and health consultations for NPL (as well as non-NPL) hazardous waste sites. The concentration data in HazDat represent the maximum concentration found in a particular environmental medium at a specific site. Concentrations were converted to standard units for calculating the estimated daily dose.

2) Calculation of geometric mean of maximum concentrations

Since the concentration data in HazDat represent the maximum concentration found per environmental medium, the geometric mean calculated in this process represents the geometric mean of the maximum concentrations found per medium. Substances were evaluated per environmental medium, and the geometric mean for these maximum concentrations was calculated for all water, soil, or air data across all sites.

The geometric mean was chosen over other methods to calculate mean concentration because the geometric mean provides a reliable estimate of average concentration and attenuates distortion of the average by extreme outlying values. Units for geometric mean concentration were converted to milligrams per kilogram (mg/kg) for soil concentrations, milligrams per liter (mg/L) for water concentrations, and milligrams per cubic meter (mg/m^3) for air concentrations. Particulates were converted from parts per million (ppm) using molecular weight of substance in the calculation. Conversion to standard units per medium allowed a comparison of all substances under consideration for the priority list.

3) Calculation of theoretical daily dose

The exposure assumptions for children (1 liter of water consumed per day, 200 milligrams of soil ingested per day, and 15 cubic meters of air breathed 26 per day) were used to assist in the determination of a theoretical daily dose. These exposure assumptions were multiplied by the geometric mean concentration for their respective media, and then added together to determine the theoretical daily dose. The theoretical daily dose is equal to the numerator of the source contribution formula.

4) Source contribution scoring

This component received 300 maximum points. The source contributions (SC) were scored according to their natural logarithms. In order to achieve a better distribution of the source contribution data, a normal-distribution approach was used. In this approach, a two-standard deviation "cutoff" is imposed, so that values above or below this cut-off receive 300 or 0 points, respectively, for this component (see the table below). This allows for better discrimination of the individual data points; the 95% of the data within two standard deviations of the mean is more widely distributed across the 300 points that are available. This approach also ensures that average values fall in the center of the distribution, and prevents a particularly low or high outlier from drawing the average away from the center. The points are assigned using the following formula:

$$\frac{(\ln \text{Min. SC Cutoff} - \ln \text{current substance's SC})}{(\ln \text{Min. SC Cutoff} - \ln \text{Max. SC cutoff})} \times 300$$

Logarithms were used in order to retain discriminatory ability across the wide range of source contributions.

Appendix Table D8 SC average and cutoffs

SC Average	Min. SC Cutoff	Max. SC Cutoff
3.34E-4	6.78E-8	1.64

3.4.2 Exposure status of populations

Information concerning documented exposure or potential exposure to a particular substance, or to environmental media in which a substance was found was also used in the exposure component. In this component, the number of reported occurrences of exposure to a substance, or exposure or potential exposure to any media containing a substance, were counted. HazDat provides information obtained from ATSDR health assessments and health consultations on exposure or potential exposure to specific substances and to media, such as drinking water, in which substances have been reported. Substances were scored differentially with respect to identification of exposure to a particular *substance,* or of exposure or potential exposure to an environmental medium containing the substance.

3.4.3 Exposure status scoring

Exposures were broken down into three categories; the assignment of points to each of these categories is presented in Table 7. Information on all the exposure categories was assessed. If there were positive occurrences in Category 1 (exposure to contaminant), then that category was considered the prevailing exposure and the substance was scored on the basis of that exposure status. If there were no occurrences in Category 1, then Category 2 (exposure to medium containing contaminant) was used to assign exposure points; if there were no occurrences in Category 1 or 2, then Category 3 was used.

A maximum of 300 points was possible for this part of the algorithm. Points within each category were distributed from the highest to the lowest exposure instances, with the maximum exposure receiving 300 points. Lead had the highest exposure in Category 1 of 490, and therefore received 300 exposure points. The assignment of points for the remainder of substances was calculated using the following formula:

$$\frac{\text{Current substance's exposure}}{\text{Maximum exposure}} \text{ X } (\text{Max. allowed points} - \text{Min. allowed points}) + \text{Min. allowed points}$$

The Max. and Min. allowed points correspond to the specific prevailing category for the substance (see the table below). For example, if a substance's prevailing exposure (from Category 1) equals 140, then its exposure points = [(153/490) x 100] + 200 = 231.

Appendix Table D9 Exposure status scoring

Exposure Status	Point Range Assignment
(1) Exposure to Contaminant	300 - 200
(2) Exposure to Medium Containing Contaminant	200 - 100
(3) Potential Exposure to Medium Containing Contaminant	100 - 1

It is noted that the design of the algorithm effectively causes high scores to be unlikely to appear in Category 2 or 3. This is because a substance that is found in numerous media pathways at numerous sites is also likely to have occurrences of exposure to the substance (Category 1). Thus, its Category 1 score prevails over its Category 2 or Category 3 score, as discussed. Due to this “masking” effect, only substances with exposure via media at a few sites have Category 2 or 3 scores that are not masked by Category 1 occurrences. Thus, exposure point scores based on Category 2 or 3 data alone are on the low end of the range of points available for those two categories. This effect on the point score is appropriate, because the documented existence of exposure to a substance (Category 1) is a considerably more reliable measure of exposure than indicators based solely on the inferred possibility of exposure via media: categories 2 and 3.

Appendix E

U.S. EPA's alternative models

1. U.S. EPA's Alternative Models

The air dispersion models listed here are alternatives to the preferred/recommended models listed in the Guideline on Air Quality Models. They can be used in regulatory applications with case-by-case justification to the Reviewing Authority. These models include:

1.1 ADAM

Air Force Dispersion Assessment Model (ADAM) is a modified box and Gaussian dispersion model which incorporates thermodynamics, chemistry, heat transfer, aerosol loading, and dense gas effects. Release scenarios include continuous and instantaneous, area and point, pressurized and unpressurized, and liquid/vapor/two-phased options.

1.2 ADMS-3

Atmospheric Dispersion Modeling System (ADMS-3) is an advanced dispersion model developed in England for calculating concentrations of pollutants emitted either continuously from point, line, volume and area sources, or discretely from point sources. The model includes algorithms which take account of the following: effects of main site building; complex terrain; wet deposition, gravitational settling and dry deposition; short term fluctuations in concentration; chemical reactions; radioactive decay and gamma-dose; plume rise as a function of distance; jets and directional releases; averaging time ranging from very short to annual; condensed plume visibility; meteorological preprocessor.

1.3 AFTOX

AFTOX is a Gaussian dispersion model that handles continuous or instantaneous, liquid or gas, elevated or surface releases from point or area sources.

Output consists of concentration contour plots, concentration at a specified location, and maximum concentration at a given elevation and time.

1.4 ASPEN

The Assessment System for Population Exposure Nationwide (ASPEN) consists of dispersion and a mapping module. The dispersion module is a Gaussian formulation based on ISCST3 for estimating ambient annual average concentrations at a set of fixed receptors within the vicinity of the emission source. The mapping module produces a concentration at each census tract. Input data needed are emissions data, meteorological data and census tract data. The Emissions Modeling System for Hazardous Pollutants (EMS-HAP) is needed to process the emission inputs into the ASPEN model or the ISC3 model. The ASPEN model was used in estimating annual ambient concentrations for air toxics pollutant in the National Air Toxics Assessment (NATA) Study.

1.5 DEGADIS

Dense Gas Dispersion (DEGADIS) is a model that simulates the dispersion at ground level of area source clouds of denser-than-air gases or aerosols released with zero momentum into the atmosphere over flat, level terrain. The model describes the dispersion processes which accompany the ensuing gravity-driven flow and entrainment of the gas into the boundary layer.

1.6 HGSYSTEM

HGSYSTEM is a collection of computer programs designed to predict the source-term and subsequent dispersion of accidental chemical releases with an emphasis on dense gas behavior.

1.7 HOTMAC and RAPTAD

HOTMAC is a model for weather forecasting used in conjunction with RAPTAD which is a 3-dimensional Lagrangian random puff model for pollutant transport and dispersion. These models are used for complex terrain, coastal regions, urban areas, and around buildings where other models fail.

1.8 HYROAD

The HYbrid ROADway Model (HYROAD) integrates three historically individual modules that simulate the effects of traffic, emissions and dispersion. The traffic module is a microscale transportation model which simulates individual vehicle movement. The emission module uses speed distributions from the traffic module to determine composite emission factors; spatial and temporal distribution of emissions is based on the vehicle operation simulations. The model tracks vehicle speed and acceleration distributions by signal phase per 10-meter roadway segment for use in both emissions distribution and for induced flows and turbulence. The dispersion module uses a Lagrangian puff formulation, along with a gridded non-uniform wind and stability field derived from traffic module outputs, to describe near-roadway dispersion characteristics. HYROAD is designed to determine hourly concentrations of carbon monoxide (CO) or other gas-phase pollutants, particulate matter (PM) and air toxics - in consultation with appropriate Reviewing Authority - from vehicle emissions at receptor locations that occur within 500 meters of the roadway intersections.

1.9 ISC3

Industrial Source Complex 3 (ISC3) is a steady-state Gaussian plume model which can be used to assess pollutant concentrations from a wide variety of sources associated with an industrial complex. This model can account for the following: settling and dry deposition of particles; downwash; point, area, line, and volume sources; plume rise as a function of downwind distance; separation of point sources; and limited terrain adjustment. ISC3 operates in both long-term and short-term modes. ISC3 also uses the Emissions Modeling System for Hazardous Pollutants (EMS-HAP) to process an emission inventory for input into the model. The Building Profile Input Program (BPIP) and the Building Profile Input Program for PRIME (BPIPPRM) can also be used with ISC3 to correctly calculate building heights (bh) and projected building widths (pbw) for simple, multi-tiered, and groups of structures. It was once accepted and used by the U.S. EPA as one of the preferred air dispersion models in Guideline on Air Quality Models, but it has been replaced with AERMOD modeling system since December 9, 2006.

1.10 ISC-PRIME

ISC-PRIME (Plume RIse Model Enhancements) is a model with building downwash incorporated into the Industrial Source Complex Short Term Model (ISCST3). In other words, it is an enhanced version of ISCST3 equipped with plume rise effect improvement.

1.11 OBODM

OBODM is an air dispersion model intended for use in evaluating the potential air quality impacts of the open burning and detonation (OB/OD) of obsolete munitions and solid propellants. OBODM uses cloud/plume rise dispersion, and deposition algorithms taken from existing models for instantaneous and quasi-continuous sources to predict the downwind transport and dispersion of pollutants released by OB/OD operations.

1.12 OZIPR

OZIPR is a one-dimensional photochemical box model that is an alternative version of the OZIP model that deals with air toxic pollutants.

1.13 PANACHE

PANACHE is an Eulerian (and Lagrangian for particulate matter), 3-dimensional finite volume fluid mechanics model designed to simulate continuous and short-term pollutant dispersion in the atmosphere, in simple or complex terrain. Emissions from both industrial and traffic sources can be input to the model. Specific features of the model are the ability to simulate very low wind speeds, and wind flow patterns around uneven terrain and high rise buildings.

1.14 PLUVUEII

PLUVUEII is a model used for estimating visual range reduction and atmospheric discoloration caused by plumes resulting from the emissions of particles, nitrogen oxides, and sulfur oxides from a single source. The model predicts the transport, dispersion, chemical reactions, optical effects and surface deposition of point or area source emissions.

1.15 SCIPUFF

Second-order Closure Integrated PUFF Model (SCIPUFF) is a Lagrangian puff dispersion model that uses a collection of Gaussian puffs to predict three-dimensional, time-dependent pollutant concentrations. In addition to the average concentration value, SCIPUFF provides a prediction of the statistical variance in the concentration field resulting from the random fluctuations in the wind field.

1.16 SDM

Shoreline Dispersion Model (SDM) is a Gaussian dispersion model used to determine ground-level concentrations from tall stationary point source emissions near a shoreline.

1.17 SLAB

SLAB model treats denser-than-air releases by solving the one-dimensional equations of momentum, conservation of mass, species, and energy, and the equation of state. SLAB handles release scenarios including ground level and elevated jets, liquid pool evaporation, and instantaneous volume sources.

2. U.S. EPA's Screening Models

These air dispersion models are screening models that are usually applied before a refined air quality model to determine if refined modeling is needed. These models include:

2.1 AERSCREEN

AERSCREEN is the screening model for AERMOD. The model will produce estimates of regulatory design concentrations without the need for meteorological data and is designed to produce concentration that are equal to or greater than the estimates produced by AERMOD with a fully developed set of meteorological and terrain data.

2.2 CTSCREEN

CTSCREEN is a Gaussian plume dispersion model designed as a screening technique for regulatory application to plume impaction assessments in complex terrain. CTSCREEN is a screening version of the CTDMPLUS model.

2.3 SCREEN3

SCREEN3 is a single source Gaussian plume model which provides maximum ground-level concentrations for point, area, flare, and volume sources, as well as concentrations in the cavity zone, and concentrations due to inversion break-up and shoreline fumigation. SCREEN3 is a screening version of the ISC3 model.

2.4 TSCREEN

Toxics Screening Model (TSCREEN) is a Gaussian model that implements the procedures to correctly analyze toxic emissions and their subsequent dispersion from one of many different types of possible releases for superfund sites. It contains 3 models: SCREEN3, PUFF, and RVD (Relief Valve Discharge).

2.5 VALLEY

VALLEY is a steady-state, complex terrain Gaussian plume dispersion algorithm designed for estimating either 24-hour or annual concentrations resulting from emissions from up to 50 (total) point and area sources.

2.6 COMPLEX1

COMPLEX1 is a multiple point source screening technique with terrain adjustment that incorporates the plume impaction algorithm of the VALLEY model. It uses sequential meteorological data, but requires fewer parameters than RTDM3.2.

2.7 RTDM3.2

Rough Terrain Diffusion Model3.2 (RTDM3.2) is a sequential Gaussian plume model designed to estimate ground-level concentrations in rough (or flat) terrain in the vicinity of one or more co-located point sources. It calculates 1-hour averages only; building wake effects cannot be modeled, only rural dispersion coefficients are available, and there is no percentile post-processor. RTDM3.2 requires on-site hourly measurements of turbulence intensity, vertical temperature difference, horizontal wind shear and wind profile exponents.

2.8 VISCREEN

VISCREEN is a model used to calculate the potential impact of a plume of specified emissions for specific transport and dispersion conditions.

Appendix F

U.S. EPA's emission factors for 27 air pollutants

This section contains one table representing U.S. EPA’s coal combustion emission factors and emission rates for 27 air pollutants used in this study. These emission factors are listed in the table below.

Appendix Table F1 U.S. EPA’s coal combustion emission factors for 27 selected pollutants

Pollutant	**Emission Factor (lb/ton)**
Ammonia	0.00171
Antimony	0.000018
Arsenic	0.00041
Barium	0.00511
Beryllium	0.000021
Cadmium	0.000051
Carbon Monoxide	1.03 (Kton/Mton)
Chromium	0.00026
Cobalt	0.0001
Copper	0.00018
2,3,7,8-TCDD	0.000000000393
Hydrogen Chloride	1.2
Lead	0.00042
Manganese	0.00049
Mercury	0.000083
Nickel	0.00028
Nitrogen Dioxide	-
Benzo(a)pyrene	0.000000038
Naphthalene	0.000013
PM_{10}	0.45 (Kton/Mton)
Selenium	0.0013
SO_2	-

Appendix Table F1 (Continued)

Pollutant	**Emission Factor (lb/ton)**
Benzene	0.0013
Carbon Tetrachloride	0.0000609
Chloroform	0.000059
Vinyl Chloride	0.0000399
Xylene	0.000037

Source: Manning (1993)

Appendix G

Slope factors and reference doses for 27 air pollutants

This section contains one table representing U.S. EPA's coal combustion emission factors for 27 air pollutants used in this study. These emission factors are listed in the table below.

Appendix Table G1 Slope factors and reference doses for 27 selected air pollutants

Pollutant	Slope Factor (per mg/kg-day)			Reference Dose (mg/kg-day)		
	Inhalation	Dermal	Oral	Inhalation	Dermal	Oral
Ammonia	-	-	-	0.0286	-	-
Antimony	-	-	-	0.0004	0.000008	0.0004
Arsenic	15.1	3.66	1.5	0.00000858	0.000123	0.0003
Barium	-	-	-	0.000143	0.014	0.2
Beryllium	8.4	430	4.3	0.00000572	0.00002	0.002
Cadmium	6.29	-	-	-	0.000005	0.001
Carbon Monoxide	-	-	-	9.7812	-	-
Chromium	42		0.003	0.0000286	0.005	0.003
Cobalt	-	-	-	0.000003432	-	-
Copper	-	-	-	0.01	0.012	0.04
2,3,7,8-TCDD	150000	-	150000	-	-	$1x10^{-9}$
HCl	-	-	-	0.00572	0	0
Lead	0.042		0.0085	0.000429	-	0.0006
Manganese	-	-	-	0.0000143	0.0056	0.14
Mercury	-	-	-	0.0000858	0.000021	0.0003
Nickel	0.84	-	-	-	0.0054	0.02
NO_2	-	-	-	0.00572	-	1
Benzo(a)-pyrene	3.08	23.5	7.3	0.41	-	0.41
Naphthalene	-	-	-	0.000858	0.016	0.02
PM_{10}	-	-	-	0.00143	-	-

Appendix Table G1 (Continued)

Pollutant	Slope Factor (per mg/kg-day)			Reference Dose (mg/kg-day)		
	Inhalation	**Dermal**	**Oral**	**Inhalation**	**Dermal**	**Oral**
Selenium	-	-	-	0.001	0.0022	0.005
SO_2	-	-	-	0.0858	-	-
Benzene	0.029	0.057	0.055	0.00858	0.00388	0.004
Carbon Tetrachloride	0.0524	0.2	0.13	-	0.000455	0.0007
Chloroform	0.0804	0.0305	0.0061	-	0.002	0.01
Vinyl Chloride	0.031	1.4	1.4	0.0286	0.003	0.003
Xylene	-	-	-	0.0286	1.84	0.2

Source: Louvar and Louvar (1998); University of Tennessee (2005)

Appendix H

Ambient air quality standards of U.S. EPA

This section contains one table showing information on ambient air quality standards of U.S EPA.

Appendix Table H1 Ambient air quality standards of U.S. EPA

Pollutant	**Ambient Air Quality Standards (ppm)**		
	1-hr Averaging Time	**8-hr Averaging Time**	**24-hr Averaging Time**
Carbon Monoxide	35	9	-
Nitrogen Dioxide	-	-	0.05
Sulfur Dioxide	-	-	0.14
Lead	-	-	-
Ozone	0.12	0.08	-
PM_{10}	0.15 (mg/m^3)	-	-

Source: Hall (1990)

Appendix I

Concentrations of 27 air pollutants at four villages

This section contains four tables illustrating information on 24-hour concentrations of 27 selected air pollutants, obtained from running CALPUFF modeling system, at four villages nearest Hingrude coal-fired power plant: Ban Khok Ta Hom, Ban Ang Dhong, Ban Nong Ya Plong and Ban Grude. This information includes average, maximum and minimum 24-hour concentrations of 27 selected air pollutants released from Hingrude coal-fired power plant.

Appendix Table I1 Concentrations of 27 selected pollutants at Ban Khok Ta Hom

Pollutant	**Concentrations at Ban Khok Ta Hom (mg/m^3)**		
	Average	**Maximum**	**Minimum**
Ammonia	2.1108×10^{-6}	1.8394×10^{-5}	2.1248×10^{-10}
Antimony	2.2224×10^{-8}	1.9365×10^{-7}	2.2370×10^{-12}
Arsenic	5.0603×10^{-9}	4.4094×10^{-8}	5.0936×10^{-11}
Barium	6.3079×10^{-6}	5.4966×10^{-5}	6.3495×10^{-10}
Beryllium	2.5842×10^{-8}	2.2518×10^{-7}	2.6012×10^{-12}
Cadmium	6.3429×10^{-8}	3.2780×10^{-7}	6.3847×10^{-12}
Carbon Monoxide	2.8005×10^{-3}	2.4403×10^{-2}	2.8190×10^{-7}
Chromium	3.2185×10^{-9}	2.8045×10^{-8}	3.2397×10^{-10}
Cobalt	1.2333×10^{-7}	1.0747×10^{-6}	1.2415×10^{-11}
Copper	2.2219×10^{-7}	1.9361×10^{-6}	2.2366×10^{-11}
2,3,7,8-TCDD	4.8512×10^{-13}	4.2272×10^{-12}	4.8831×10^{-17}
Hydrogen Chloride	1.4813×10^{-3}	1.2908×10^{-2}	1.4911×10^{-7}
Lead	5.1918×10^{-7}	4.5240×10^{-6}	5.2260×10^{-11}
Manganese	5.9887×10^{-7}	5.2610×10^{-6}	6.0773×10^{-11}
Mercury	1.0243×10^{-7}	8.9252×10^{-7}	1.0310×10^{-11}
Nickel	3.4534×10^{-7}	3.0092×10^{-6}	3.4761×10^{-11}
Nitrogen Dioxide	1.4095×10^{-2}	1.2282×10^{-1}	1.4188×10^{-6}
Benzo(a)pyrene	4.6914×10^{-11}	4.0880×10^{-10}	4.7223×10^{-15}
Naphthalene	1.6045×10^{-8}	1.3981×10^{-7}	1.6151×10^{-12}
PM_{10}	1.2236×10^{-3}	1.0662×10^{-2}	1.2316×10^{-7}
Selenium	1.6045×10^{-6}	1.3981×10^{-5}	1.6151×10^{-10}

Appendix Table I1 (Continued)

Pollutant	24 Hours Concentrations at Ban Khok Ta Hom (mg/m^3)		
	Average	Maximum	Minimum
SO_2	2.7486 x10^{-2}	2.3951 x10^{-1}	2.7667 x10^{-6}
Benzene	1.6045 x10^{-6}	1.3981 x10^{-5}	1.6151 x10^{-10}
CCl_4	7.4567 x10^{-8}	6.5506 x10^{-7}	7.5671 x10^{-12}
Chloroform	7.2827 x10^{-8}	6.3459 x10^{-7}	7.3306 x10^{-12}
Vinyl Chloride	4.9254 x10^{-8}	4.2919 x10^{-7}	4.9579 x10^{-12}
Xylene	4.5669 x10^{-8}	3.9795 x10^{-7}	4.5970 x10^{-12}

Appendix Table I2 Concentrations of 27 selected pollutants at Ban Ang Dhong

Pollutant	**Concentrations at Ban Ang Dhong (mg/m^3)**		
	Average	**Maximum**	**Minimum**
Ammonia	1.4005×10^{-6}	6.3453×10^{-6}	2.2693×10^{-8}
Antimony	1.4745×10^{-8}	6.6804×10^{-8}	2.3892×10^{-10}
Arsenic	3.3575×10^{-7}	1.5211×10^{-8}	5.4400×10^{-9}
Barium	4.1853×10^{-9}	1.8962×10^{-5}	6.7813×10^{-8}
Beryllium	1.7146×10^{-8}	7.7679×10^{-8}	2.7781×10^{-10}
Cadmium	4.2085×10^{-8}	1.4031×10^{-7}	6.8190×10^{-10}
Carbon Monoxide	1.8581×10^{-3}	8.4183×10^{-3}	3.0107×10^{-5}
Chromium	2.1354×10^{-10}	9.6746×10^{-9}	3.4600×10^{-11}
Cobalt	8.1832×10^{-8}	3.7074×10^{-7}	1.3259×10^{-9}
Copper	1.4143×10^{-7}	6.6790×10^{-7}	2.3887×10^{-9}
2,3,7,8-TCDD	3.2187×10^{-13}	1.4583×10^{-12}	5.2152×10^{-15}
Hydrogen Chloride	9.8286×10^{-4}	4.4529×10^{-3}	1.5925×10^{-5}
Lead	3.4447×10^{-7}	1.5606×10^{-6}	5.5814×10^{-9}
Manganese	4.0059×10^{-7}	1.8149×10^{-6}	6.4906×10^{-9}
Mercury	6.7959×10^{-8}	3.0789×10^{-7}	1.1011×10^{-9}
Nickel	2.1894×10^{-7}	1.0381×10^{-6}	3.7125×10^{-9}
Nitrogen Dioxide	9.3522×10^{-3}	4.2370×10^{-2}	1.5153×10^{-4}
Benzo(a)pyrene	3.1127×10^{-11}	1.4102×10^{-10}	5.0435×10^{-13}
Naphthalene	1.0646×10^{-8}	4.8232×10^{-8}	1.7249×10^{-10}
PM_{10}	8.1184×10^{-4}	3.6780×10^{-3}	1.3154×10^{-5}
Selenium	1.0646×10^{-6}	4.8232×10^{-6}	1.7249×10^{-8}
SO_2	1.8237×10^{-2}	8.2622×10^{-2}	2.9549×10^{-4}
Benzene	1.0646×10^{-6}	4.8232×10^{-6}	1.7249×10^{-8}
CCl_4	4.9879×10^{-8}	2.2598×10^{-7}	8.0817×10^{-10}
Chloroform	4.8320×10^{-8}	2.1891×10^{-7}	7.8292×10^{-10}
Vinyl Chloride	3.2680×10^{-8}	1.4806×10^{-7}	5.2950×10^{-10}
Xylene	3.0301×10^{-8}	1.3728×10^{-7}	4.9097×10^{-10}

Appendix Table I3 Concentrations of 27 selected pollutants at Ban Nong Ya Plong

Pollutant	Concentrations at Ban Nong Ya Plong (mg/m^3)		
	Average	**Maximum**	**Minimum**
Ammonia	1.8326 x10^{-6}	7.2429 x10^{-6}	4.3939 x10^{-9}
Antimony	2.0126 x10^{-8}	7.6258 x10^{-8}	4.6262 x10^{-11}
Arsenic	4.5825 x10^{-9}	1.7364 x10^{-8}	1.0534 x10^{-11}
Barium	5.7124 x10^{-6}	2.1645 x10^{-5}	1.3130 x10^{-8}
Beryllium	2.3402 x10^{-8}	8.8672 x10^{-8}	5.3793 x10^{-11}
Cadmium	5.7441 x10^{-8}	1.7765 x10^{-7}	1.3204 x10^{-10}
Carbon Monoxide	2.5361 x10^{-3}	9.6096 x10^{-3}	5.8297 x10^{-6}
Chromium	2.9146 x10^{-9}	1.1044 x10^{-8}	6.6997 x10^{-10}
Cobalt	1.1169 x10^{-7}	4.2321 x10^{-7}	2.5674 x10^{-10}
Copper	2.0121 x10^{-7}	7.6242 x10^{-7}	4.6252 x10^{-10}
2,3,7,8-TCDD	4.3932 x10^{-13}	1.6646 x10^{-12}	1.0098 x10^{-15}
Hydrogen Chloride	1.3415 x10^{-3}	5.0830 x10^{-3}	3.0836 x10^{-6}
Lead	5.0149 x10^{-7}	1.7815 x10^{-6}	1.0808 x10^{-9}
Manganese	5.4493 x10^{-7}	2.0717 x10^{-6}	1.2568 x10^{-9}
Mercury	9.2756 x10^{-8}	3.5146 x10^{-7}	2.1322 x10^{-10}
Nickel	3.1274 x10^{-7}	1.1850 x10^{-6}	7.1887 x10^{-10}
Nitrogen Dioxide	1.2765 x10^{-2}	4.8367 x10^{-2}	2.9342 x10^{-5}
Benzo(a)pyrene	4.2485 x10^{-11}	1.6098 x10^{-10}	9.7659 x10^{-14}
Naphthalene	1.4530 x10^{-8}	5.5057 x10^{-8}	3.3401 x10^{-11}
PM_{10}	1.1081 x10^{-3}	4.1985 x10^{-3}	2.5471 x10^{-6}
Selenium	1.4530 x10^{-6}	5.5057 x10^{-6}	3.3401 x10^{-9}
SO_2	2.4891 x10^{-2}	9.4315 x10^{-2}	5.7216 x10^{-5}
Benzene	1.4530 x10^{-6}	5.5057 x10^{-6}	3.3401 x10^{-9}
CCl_4	6.8078 x10^{-8}	2.5796 x10^{-7}	1.5649 x10^{-10}
Chloroform	6.5950 x10^{-8}	2.4989 x10^{-7}	1.5160 x10^{-10}
Vinyl Chloride	4.4604 x10^{-8}	1.6901 x10^{-7}	1.0253 x10^{-10}
Xylene	4.1358 x10^{-8}	1.5671 x10^{-7}	9.5067 x10^{-11}

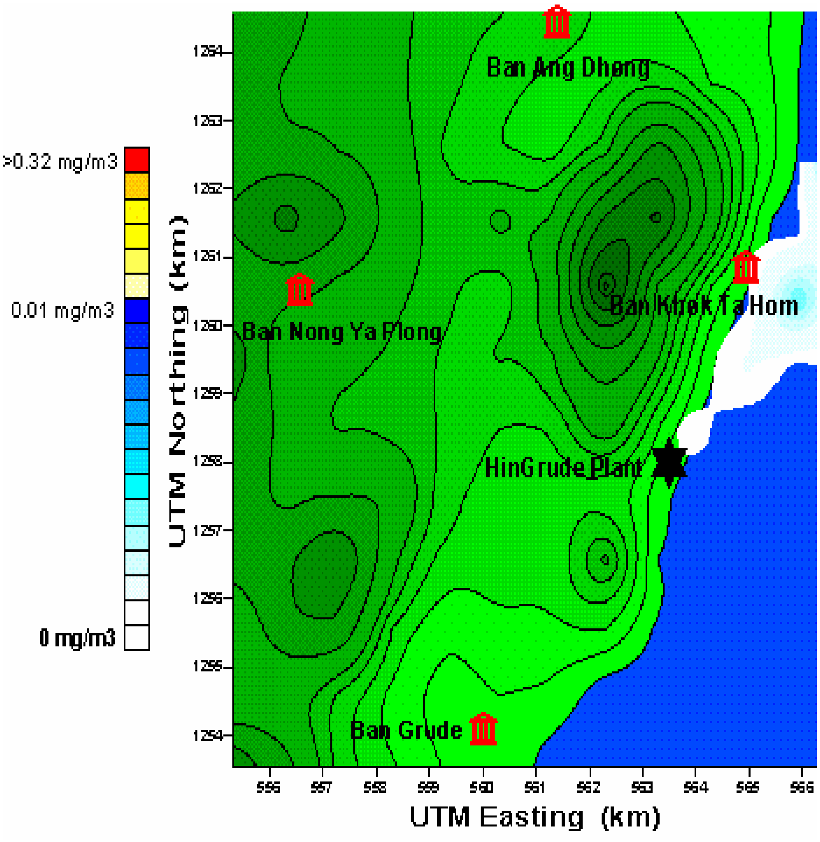
Appendix Table I4 Concentrations of 27 selected pollutants at Ban Grude

Pollutant	Concentrations at Ban Grude (mg/m^3)		
	Average	Maximum	Minimum
Ammonia	5.2587×10^{-7}	4.2570×10^{-6}	2.5788×10^{-9}
Antimony	4.9305×10^{-9}	4.4821×10^{-8}	2.7149×10^{-11}
Arsenic	4.9305×10^{-9}	1.0206×10^{-8}	6.1818×10^{-10}
Barium	1.3995×10^{-6}	1.2722×10^{-5}	7.7060×10^{-9}
Beryllium	5.7331×10^{-9}	5.2117×10^{-8}	3.1569×10^{-11}
Cadmium	1.4072×10^{-8}	7.8080×10^{-8}	7.7487×10^{-11}
Carbon Monoxide	6.2131×10^{-4}	5.6481×10^{-3}	3.4212×10^{-6}
Chromium	7.1404×10^{-10}	6.4910×10^{-9}	3.9318×10^{-11}
Cobalt	2.7363×10^{-8}	2.4874×10^{-7}	1.5067×10^{-10}
Copper	4.9294×10^{-8}	4.4811×10^{-7}	2.7144×10^{-10}
2,3,7,8-TCDD	1.0763×10^{-13}	9.7839×10^{-13}	5.9263×10^{-16}
Hydrogen Chloride	3.2865×10^{-4}	2.9876×10^{-3}	1.8096×10^{-6}
Lead	1.1518×10^{-7}	1.0471×10^{-6}	6.3425×10^{-10}
Manganese	1.3395×10^{-7}	1.2177×10^{-6}	7.3756×10^{-10}
Mercury	2.2724×10^{-8}	2.0657×10^{-7}	1.2513×10^{-10}
Nickel	8.7819×10^{-8}	6.9648×10^{-7}	4.2188×10^{-10}
Nitrogen Dioxide	3.1272×10^{-3}	2.8428×10^{-2}	1.7219×10^{-5}
Benzo(a)pyrene	1.0408×10^{-11}	9.4617×10^{-11}	5.7312×10^{-14}
Naphthalene	3.5598×10^{-9}	3.2360×10^{-8}	1.9601×10^{-11}
PM_{10}	2.7146×10^{-4}	2.4677×10^{-3}	1.4948×10^{-6}
Selenium	3.5598×10^{-7}	3.2360×10^{-6}	1.9601×10^{-9}
SO_2	6.0980×10^{-3}	5.5434×10^{-2}	3.3578×10^{-5}
Benzene	3.5598×10^{-7}	3.2360×10^{-6}	1.9601×10^{-9}
CCl_4	1.6678×10^{-8}	1.5161×10^{-7}	9.1837×10^{-11}
Chloroform	1.6157×10^{-8}	1.4688×10^{-7}	8.8967×10^{-11}
Vinyl Chloride	1.0927×10^{-8}	9.9336×10^{-8}	6.0170×10^{-11}
Xylene	1.0132×10^{-8}	9.2106×10^{-8}	5.5791×10^{-11}

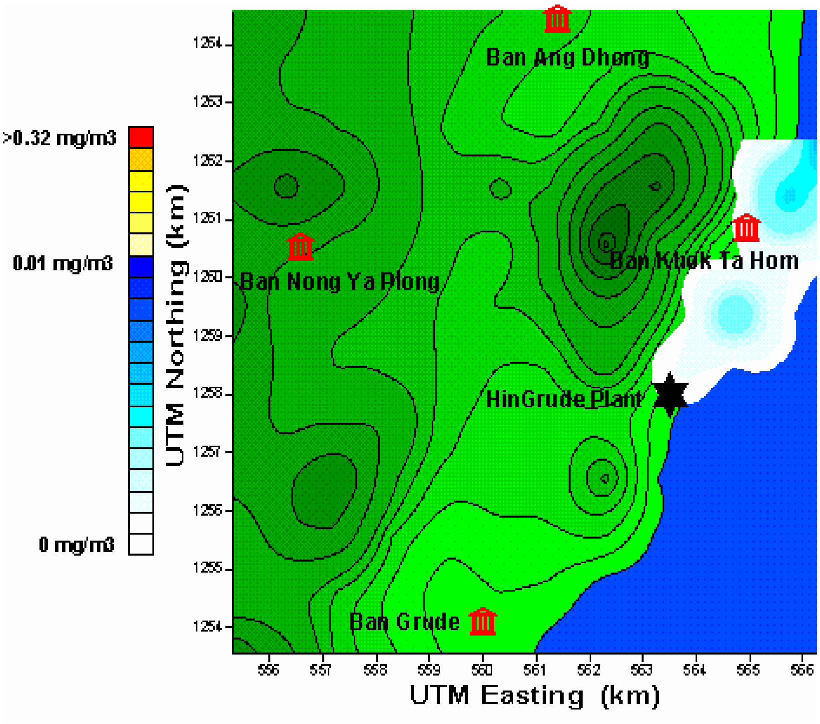
Appendix J

Hourly typical dispersion graphics of NO_2, PM_{10} and SO_2

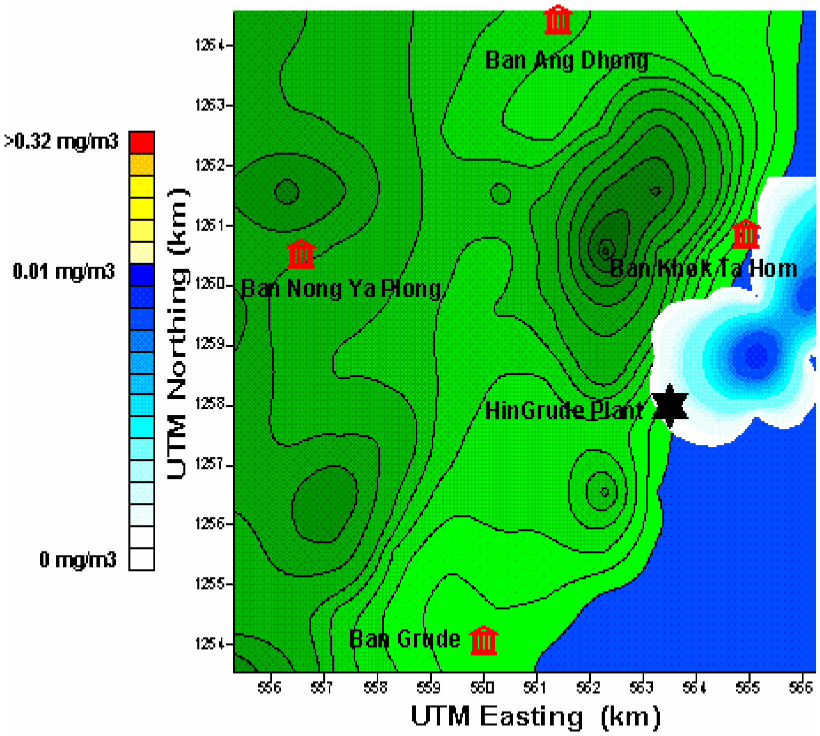
This section contains 216 figures representing hourly typical dispersion graphics of NO_2, PM_{10} and SO_2 for 24 hours in three seasons: winter, summer and rainy season. These dispersion graphics are shown in the following figures.



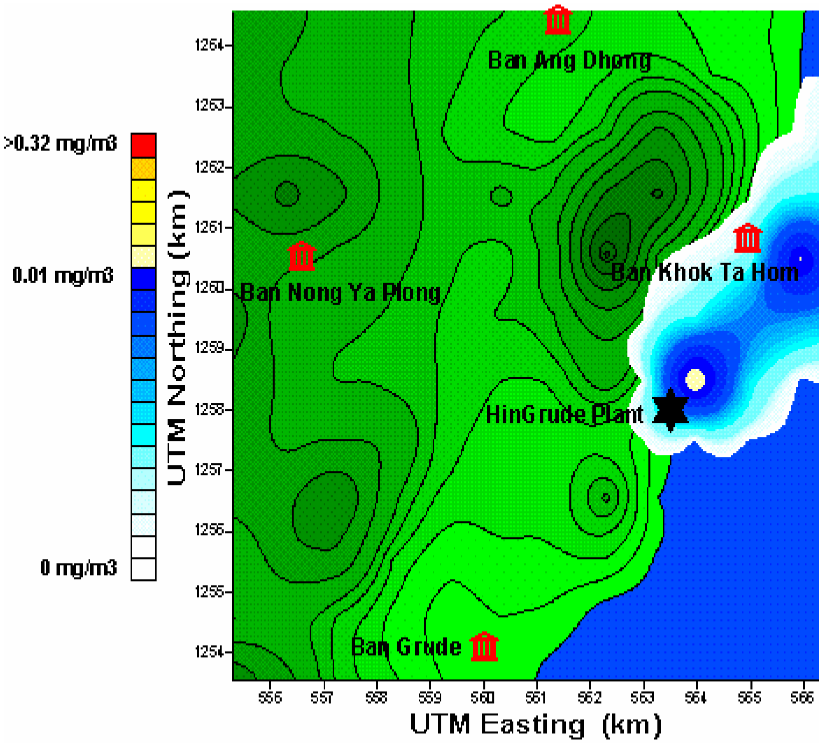
Appendix Figure J1 1st hour dispersion of NO_2 in winter



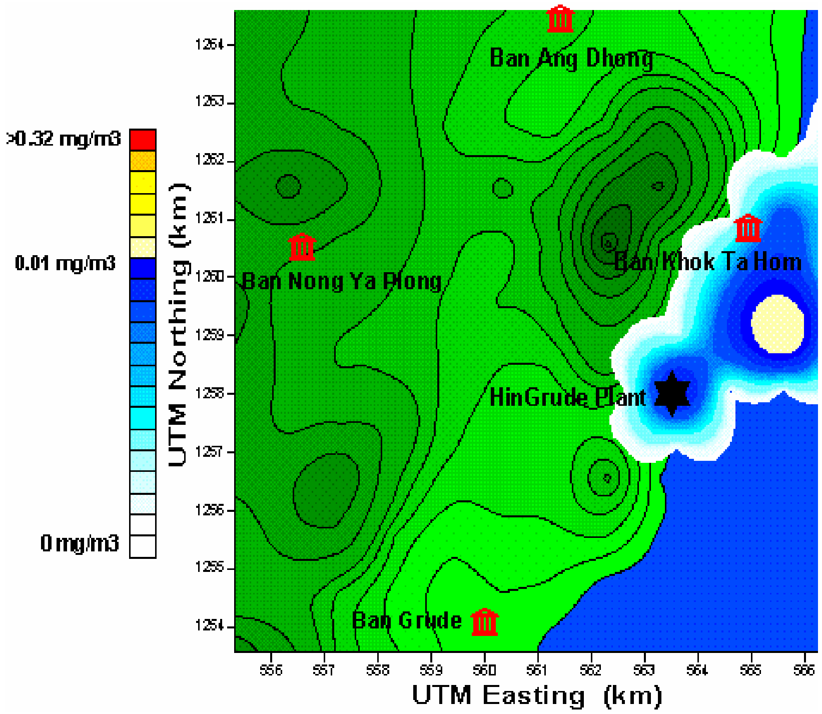
Appendix Figure J2 2nd hour dispersion of NO_2 in winter



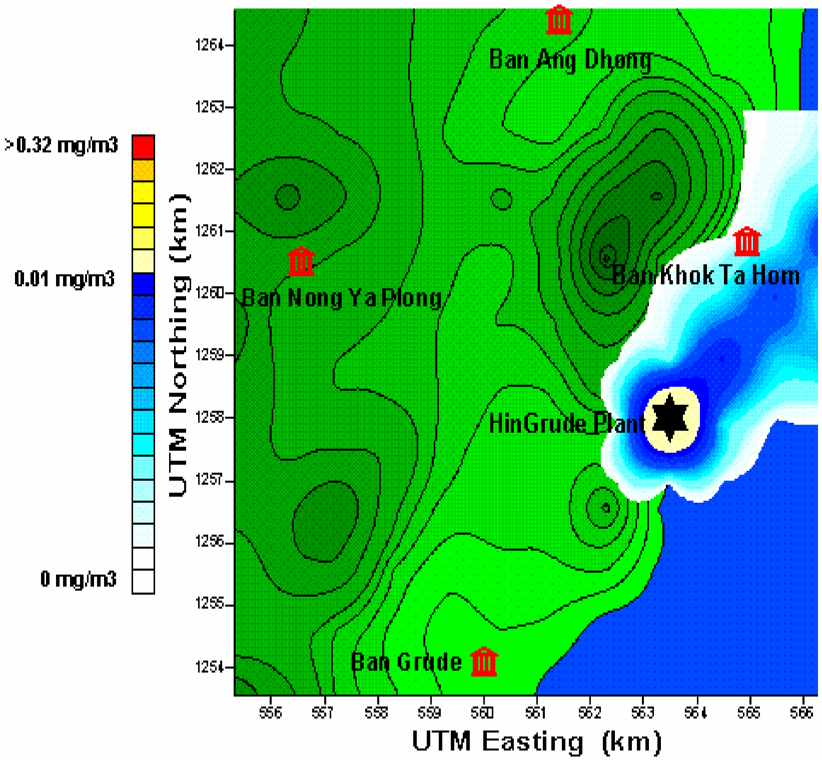
Appendix Figure J3 3rd hour dispersion of NO_2 in winter



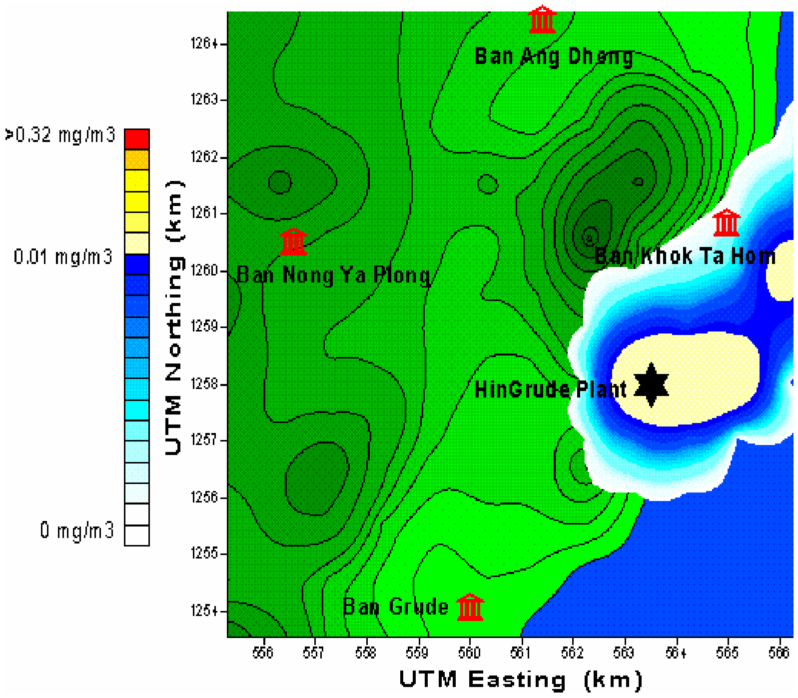
Appendix Figure J4 4th hour dispersion of NO_2 in winter



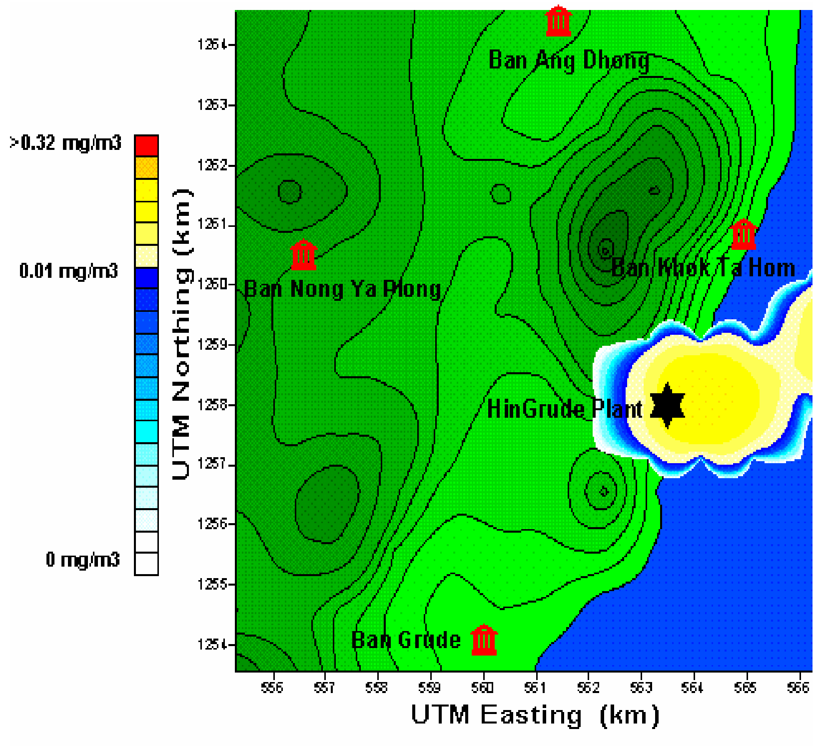
Appendix Figure J5 5th hour dispersion of NO_2 in winter



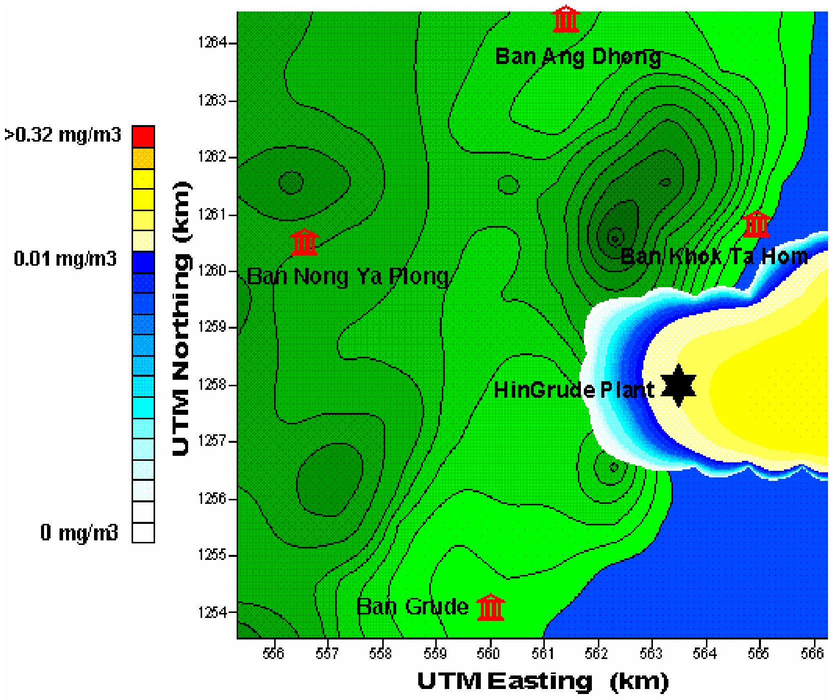
Appendix Figure J6 6th hour dispersion of NO_2 in winter



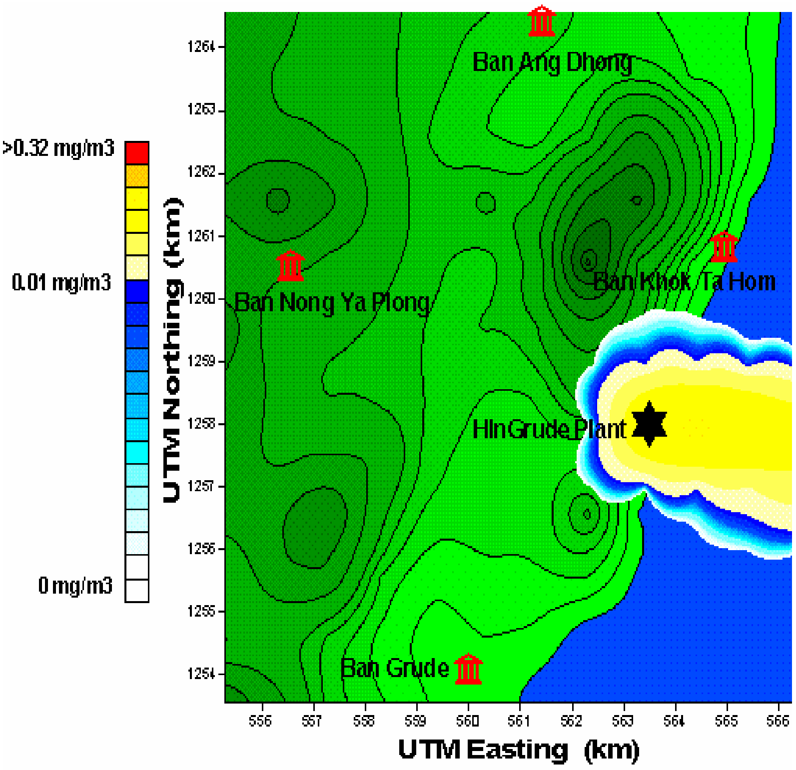
Appendix Figure J7 7th hour dispersion of NO_2 in winter



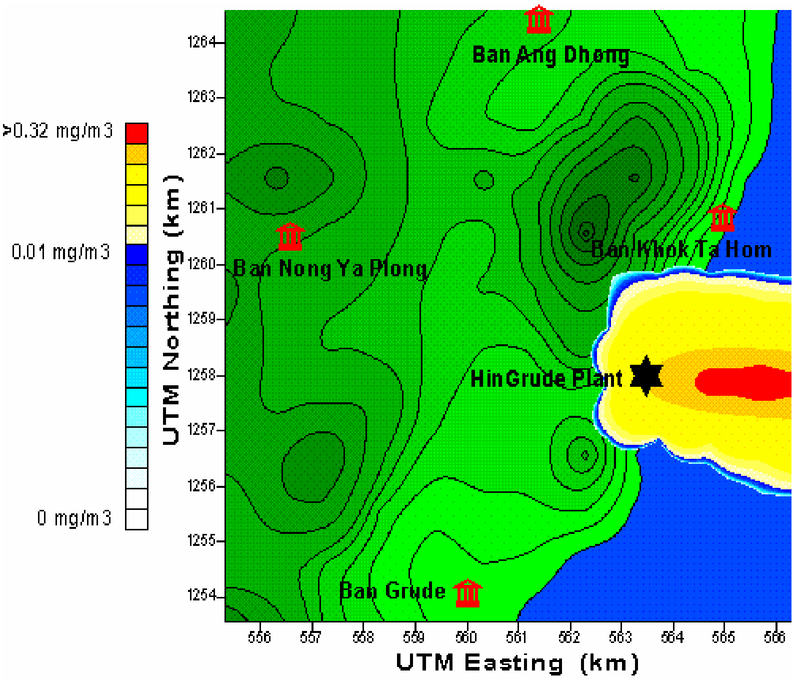
Appendix Figure J8 8th hour dispersion of NO_2 in winter



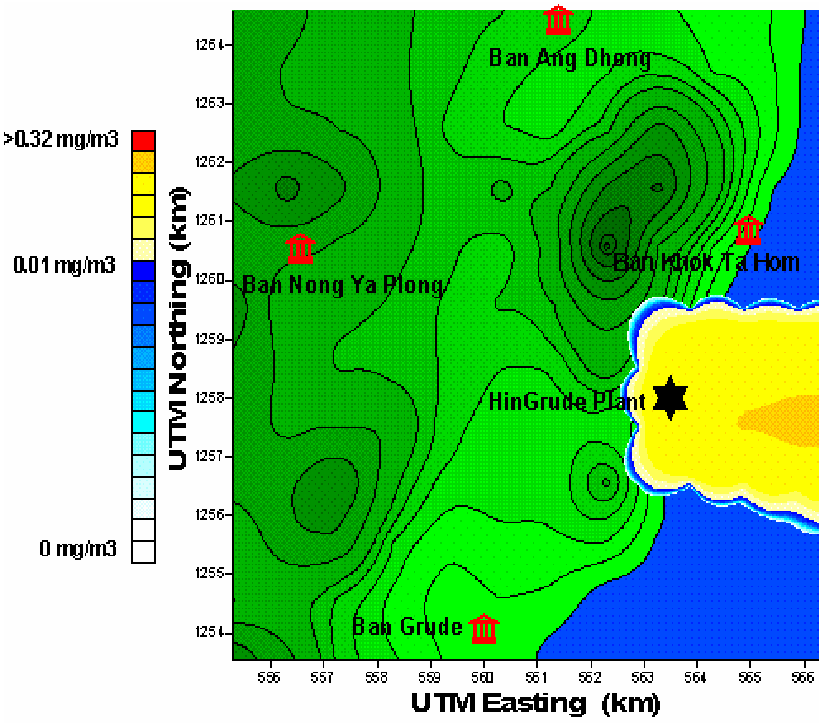
Appendix Figure J9 9th hour dispersion of NO_2 in winter



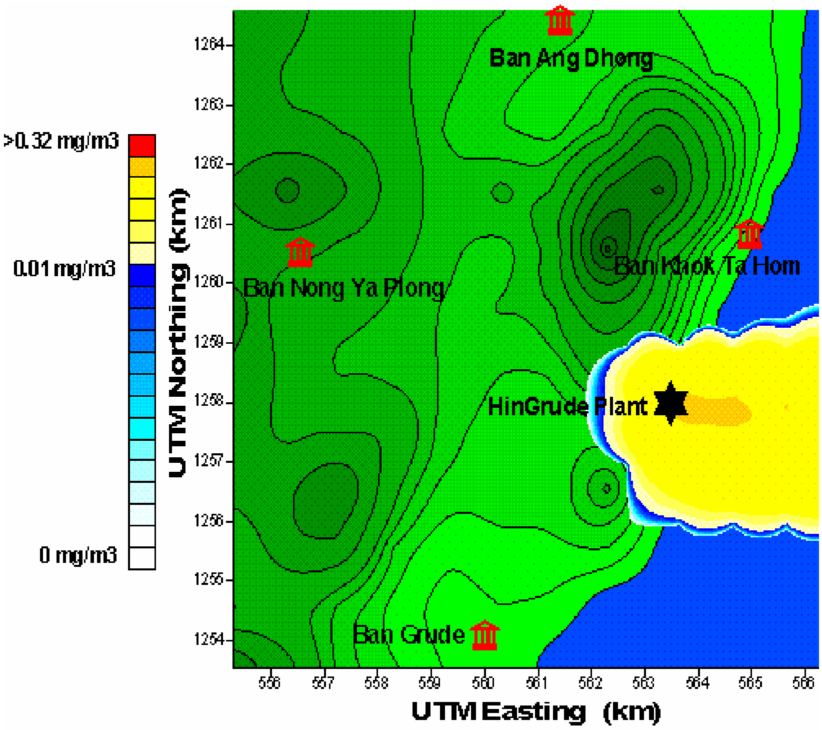
Appendix Figure J10 10th hour dispersion of NO_2 in winter



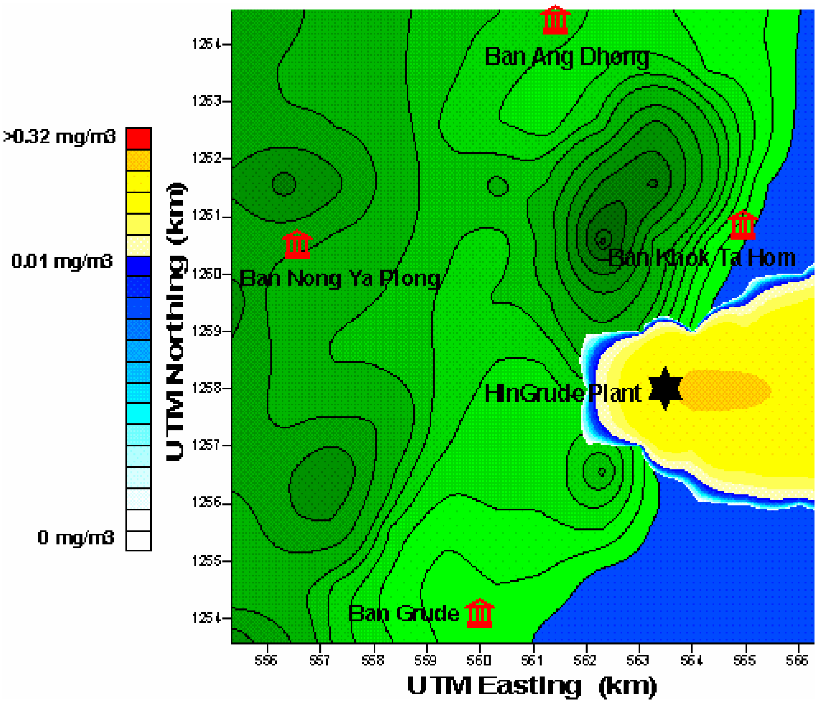
Appendix Figure J11 11th hour dispersion of NO_2 in winter



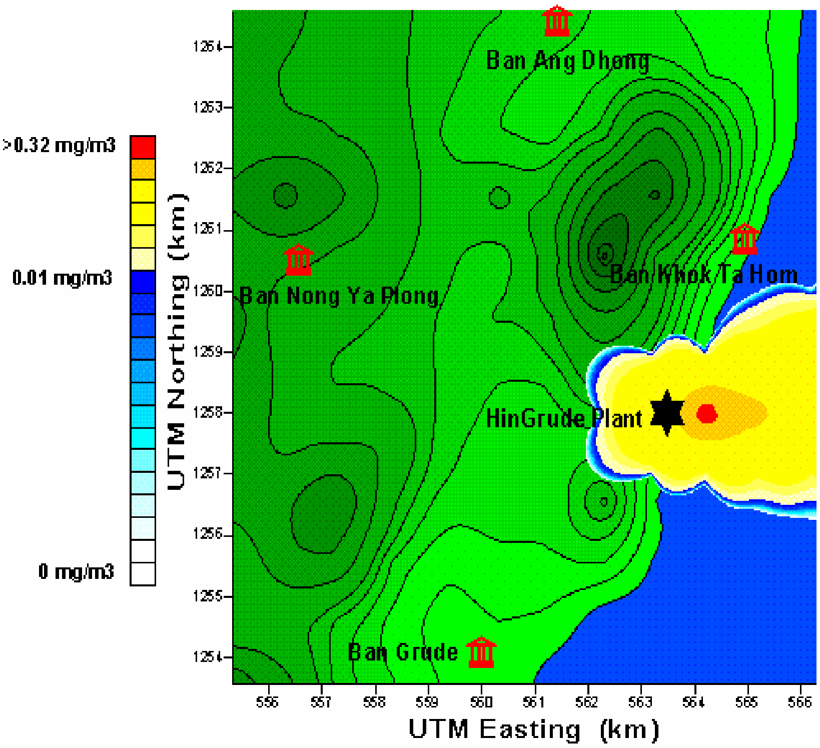
Appendix Figure J12 12th hour dispersion of NO_2 in winter



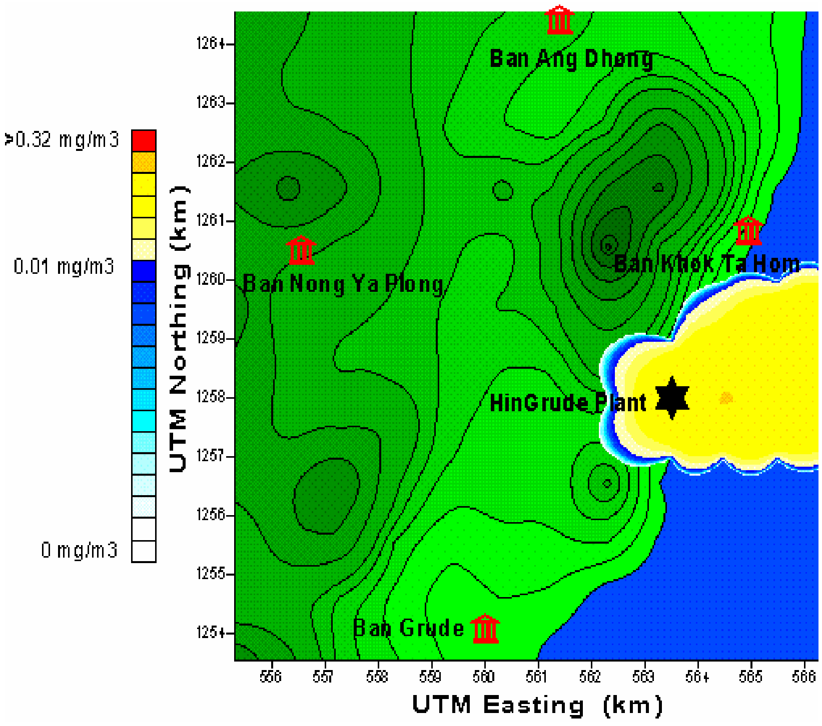
Appendix Figure J13 13th hour dispersion of NO_2 in winter



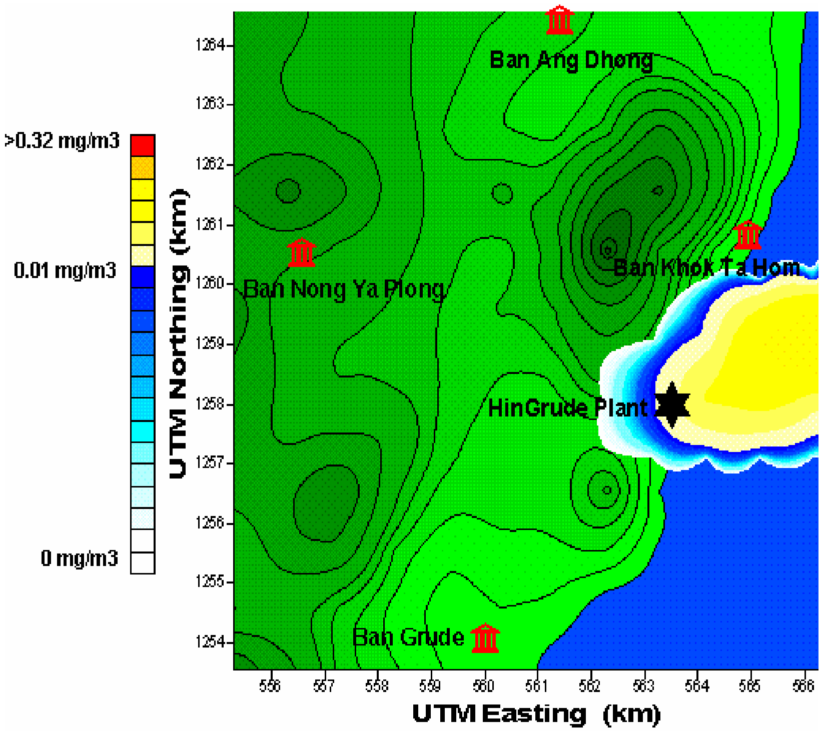
Appendix Figure J14 14th hour dispersion of NO_2 in winter



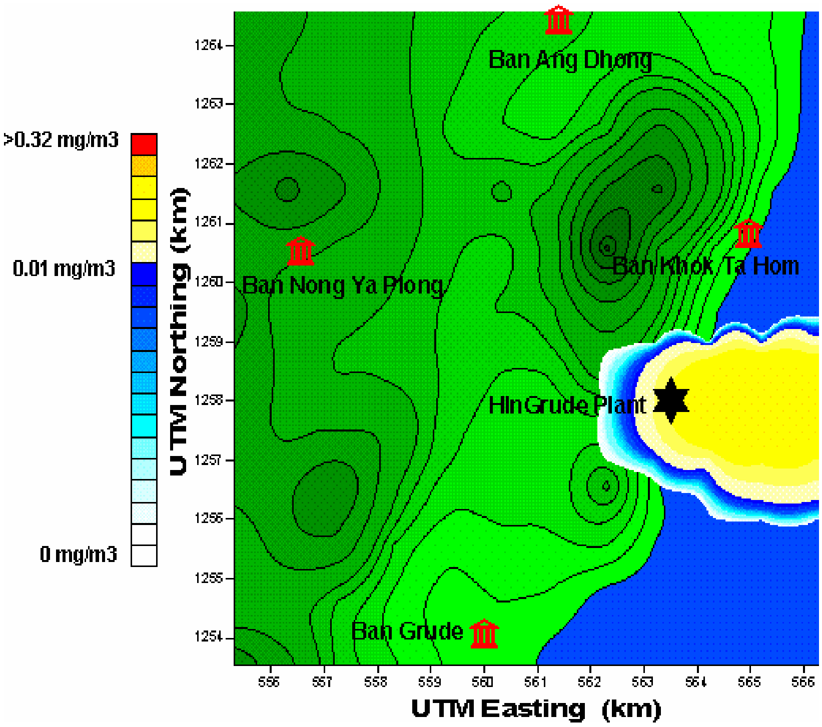
Appendix Figure J15 15th hour dispersion of NO_2 in winter



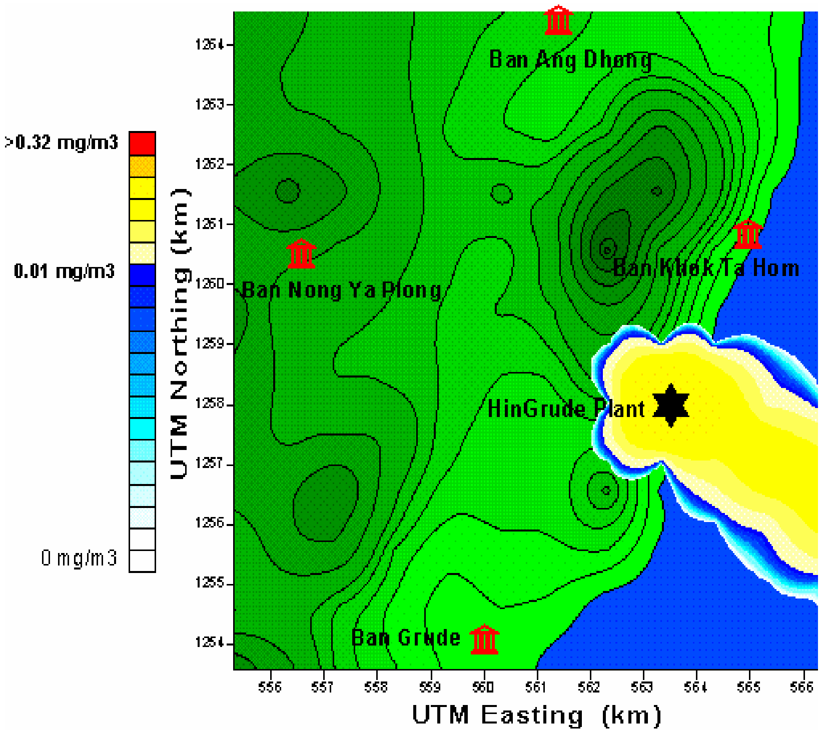
Appendix Figure J16 16th hour dispersion of NO_2 in winter



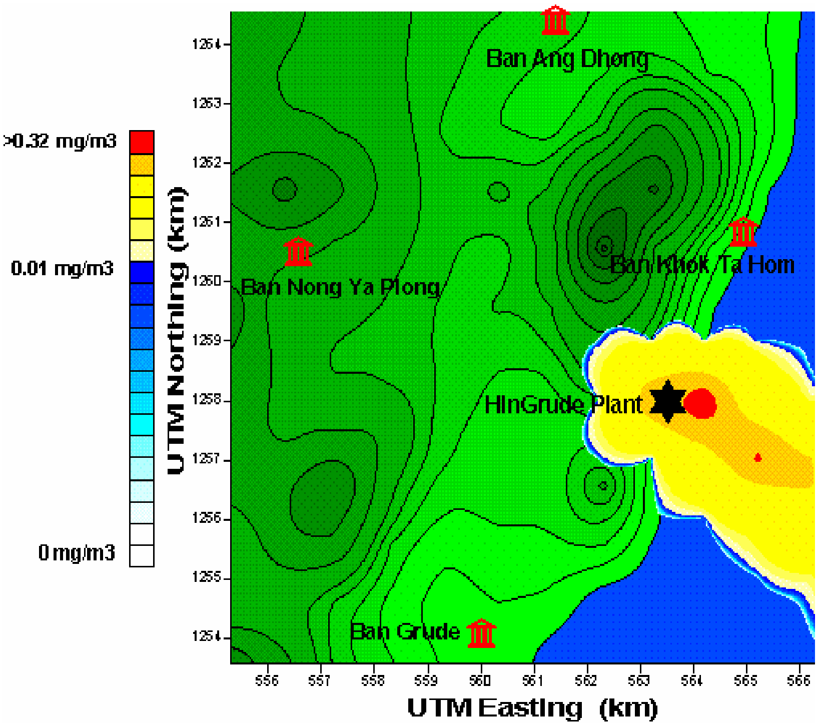
Appendix Figure J17 17th hour dispersion of NO_2 in winter



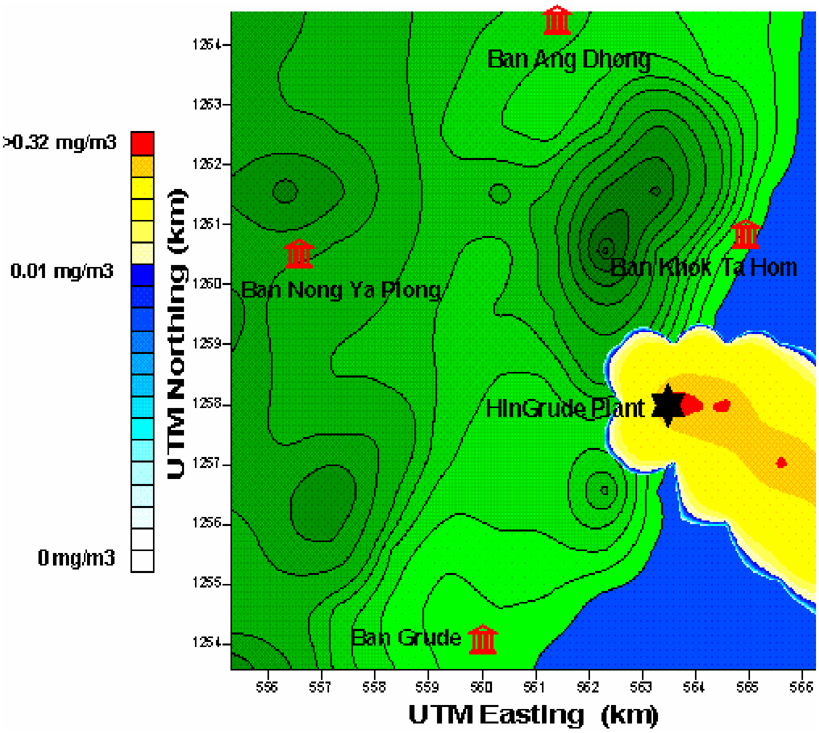
Appendix Figure J18 18th hour dispersion of NO_2 in winter



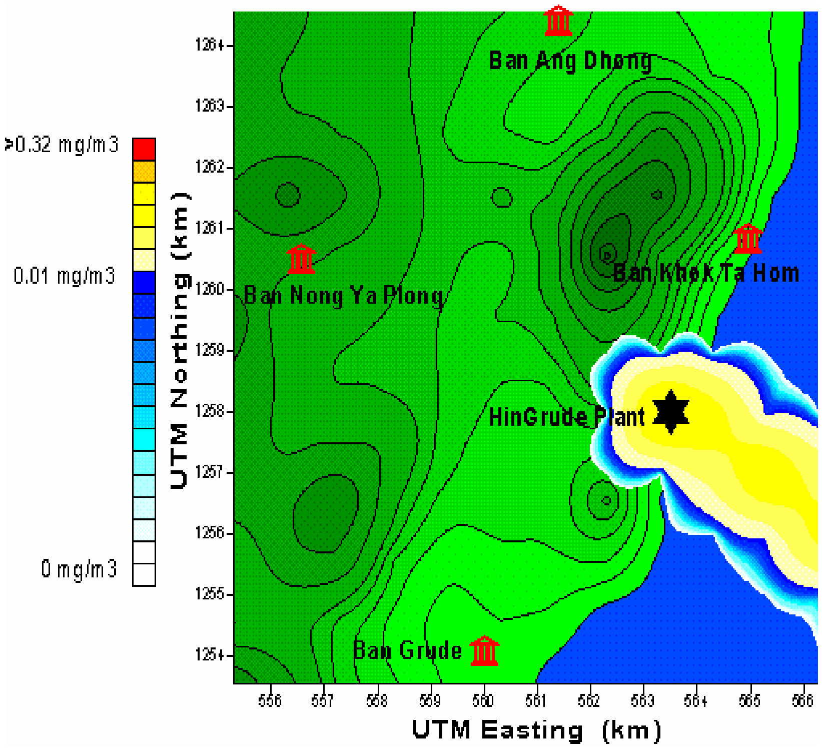
Appendix Figure J19 19th hour dispersion of NO_2 in winter



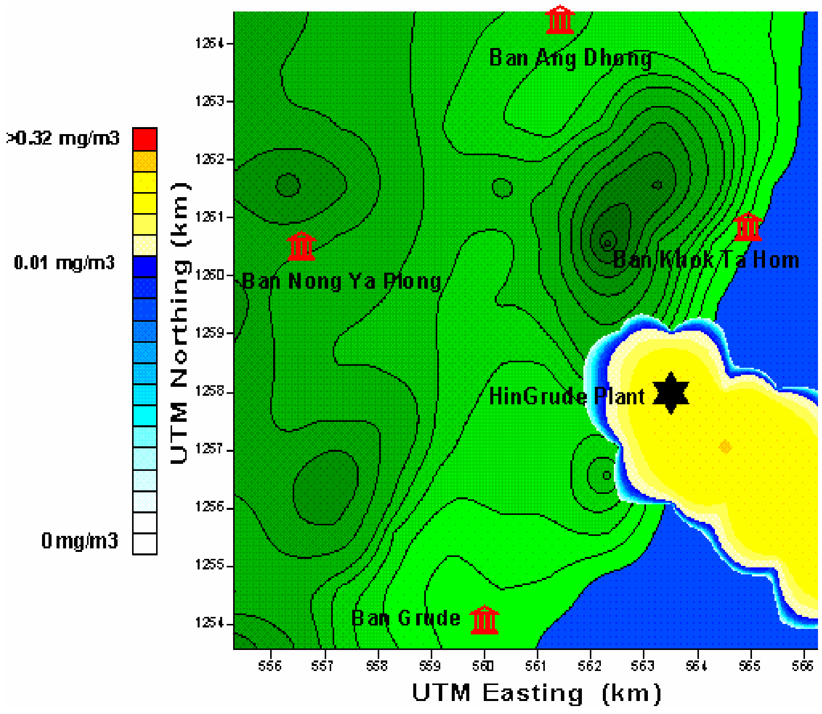
Appendix Figure J20 20th hour dispersion of NO_2 in winter



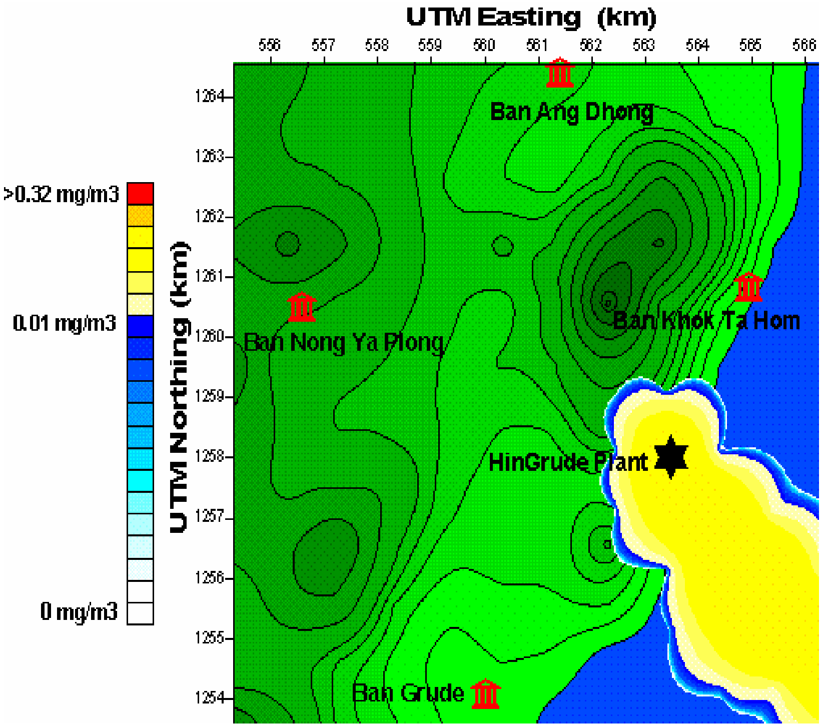
Appendix Figure J21 21st hour dispersion of NO_2 in winter



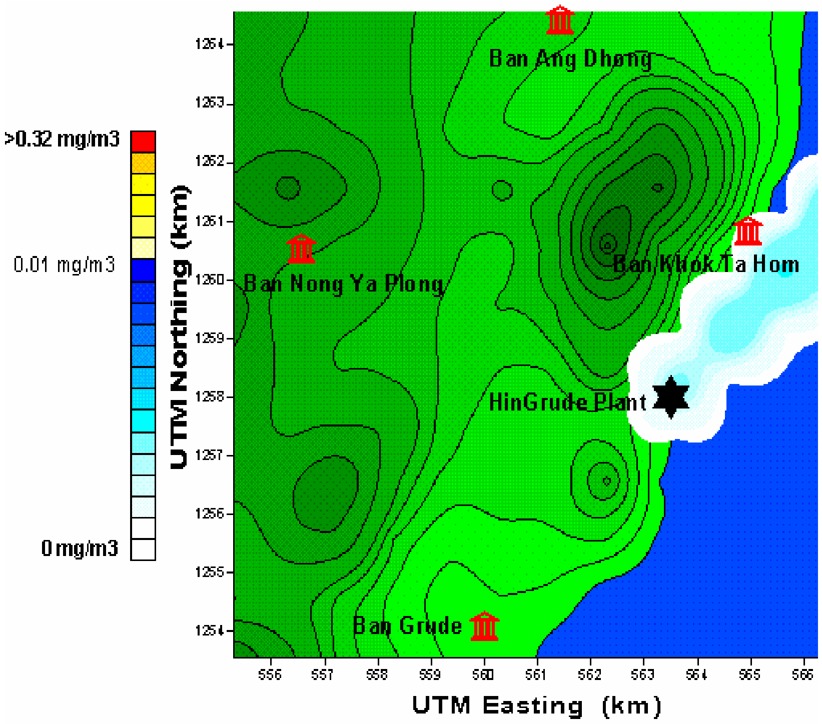
Appendix Figure J22 22nd hour dispersion of NO_2 in winter



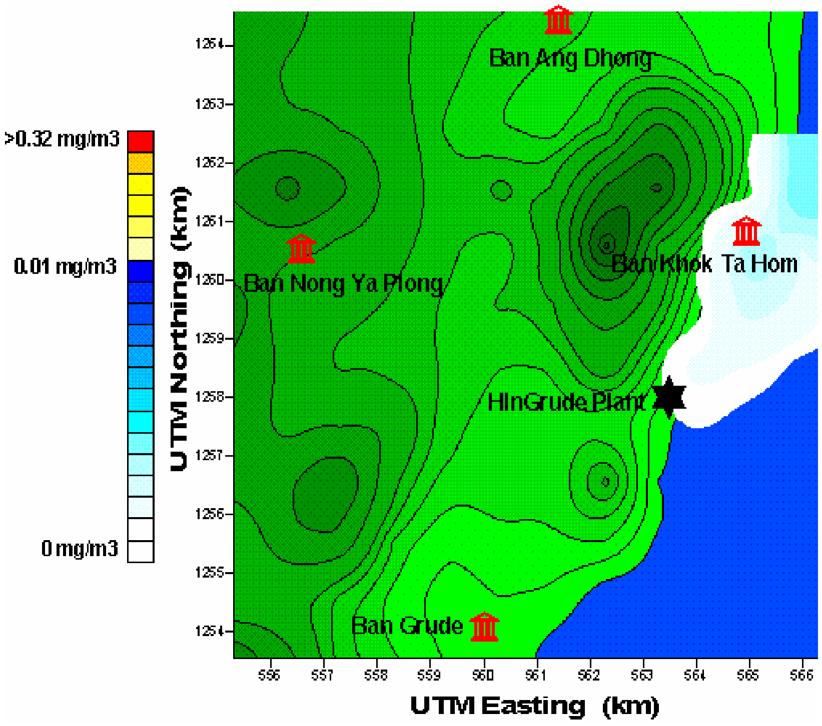
Appendix Figure J23 23rd hour dispersion of NO_2 in winter



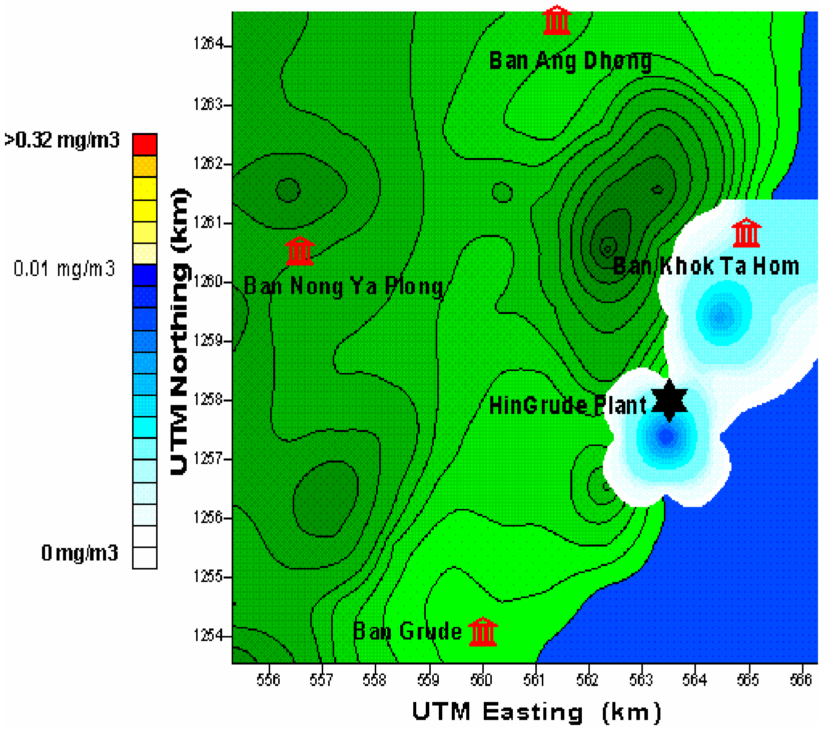
Appendix Figure J24 24th hour dispersion of NO_2 in winter



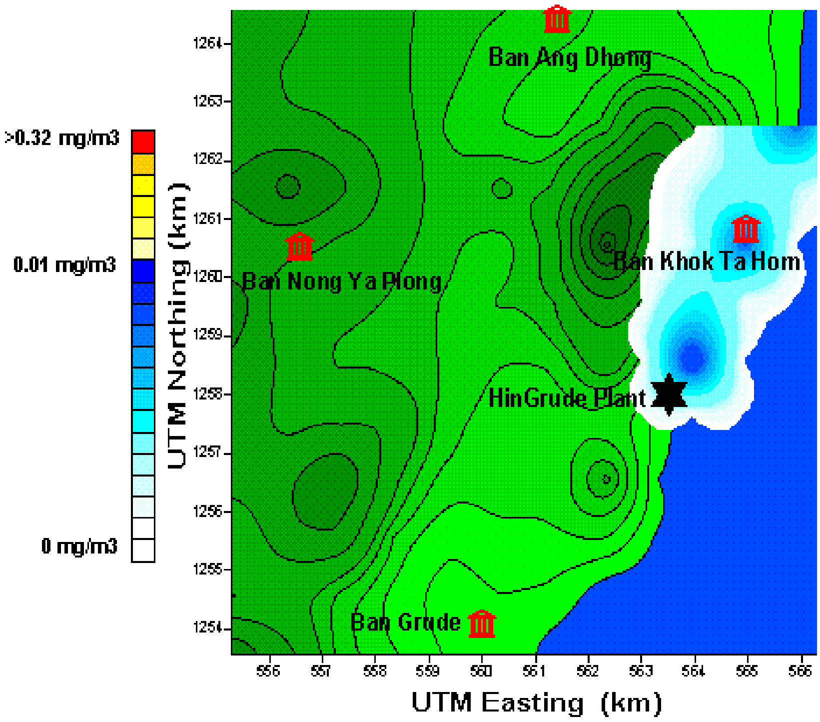
Appendix Figure J25 1st hour dispersion of NO_2 in summer



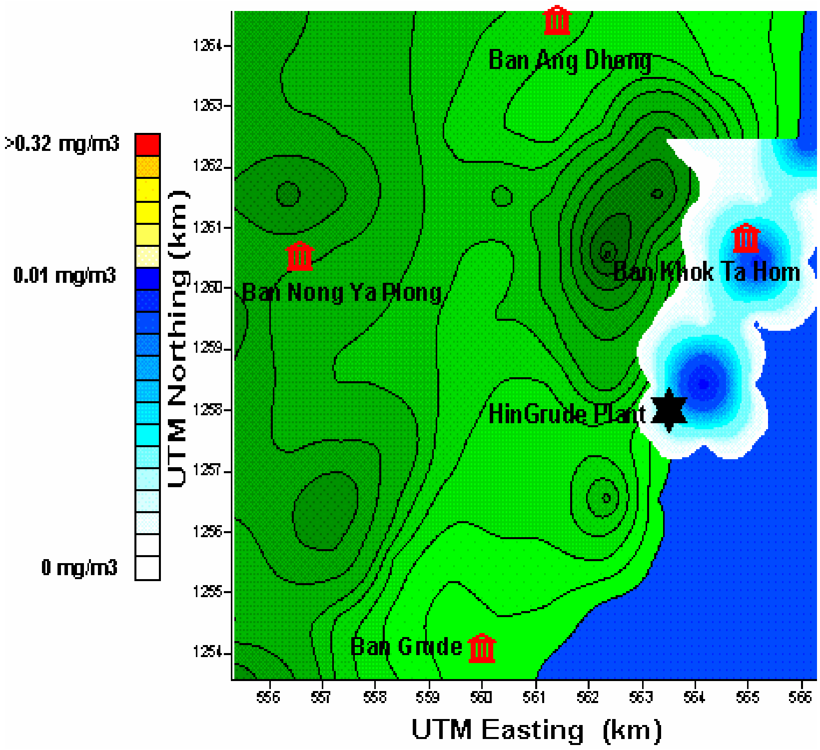
Appendix Figure J26 2nd hour dispersion of NO_2 in summer



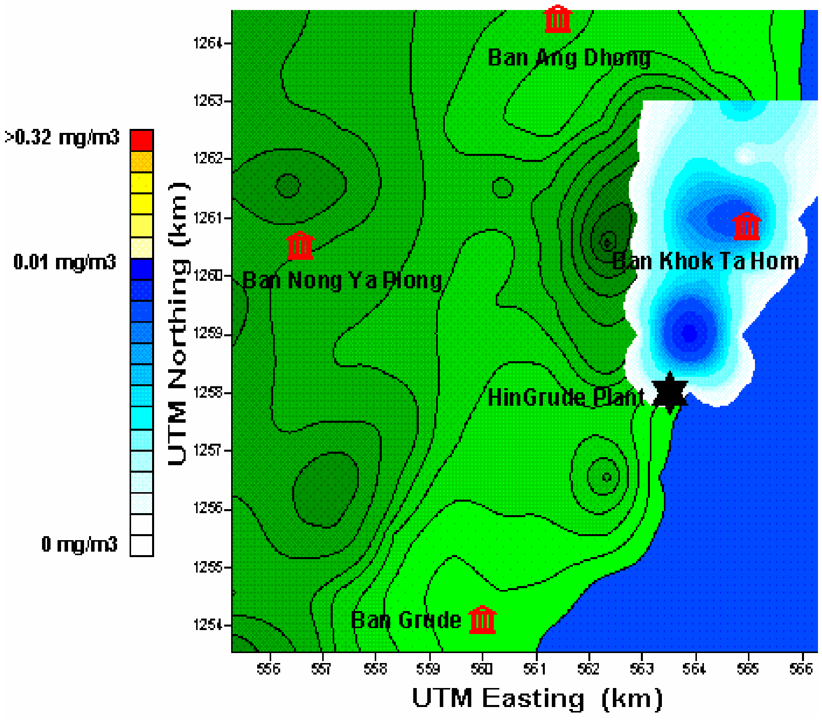
Appendix Figure J27 3rd hour dispersion of NO_2 in summer



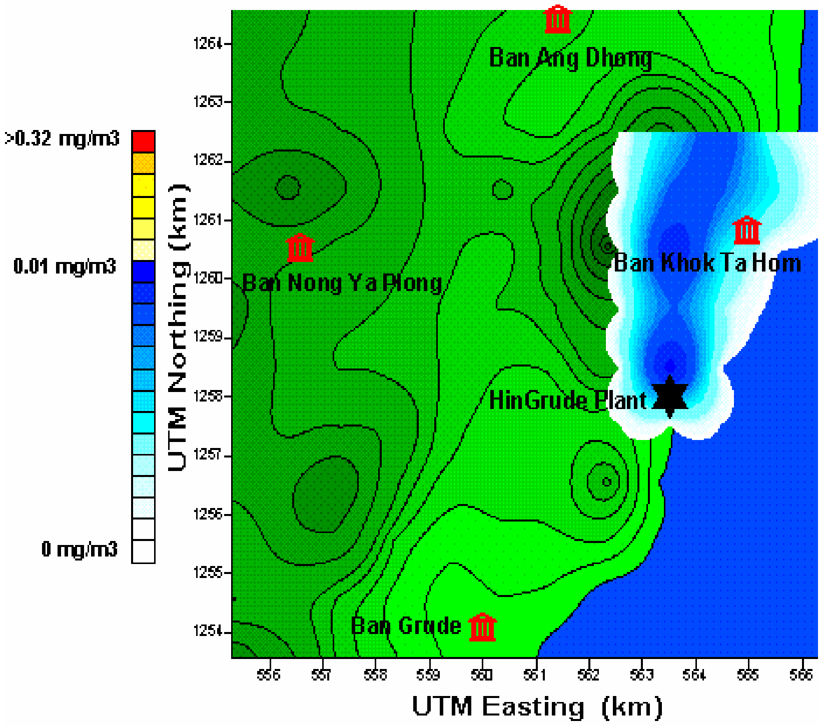
Appendix Figure J28 4th hour dispersion of NO_2 in summer



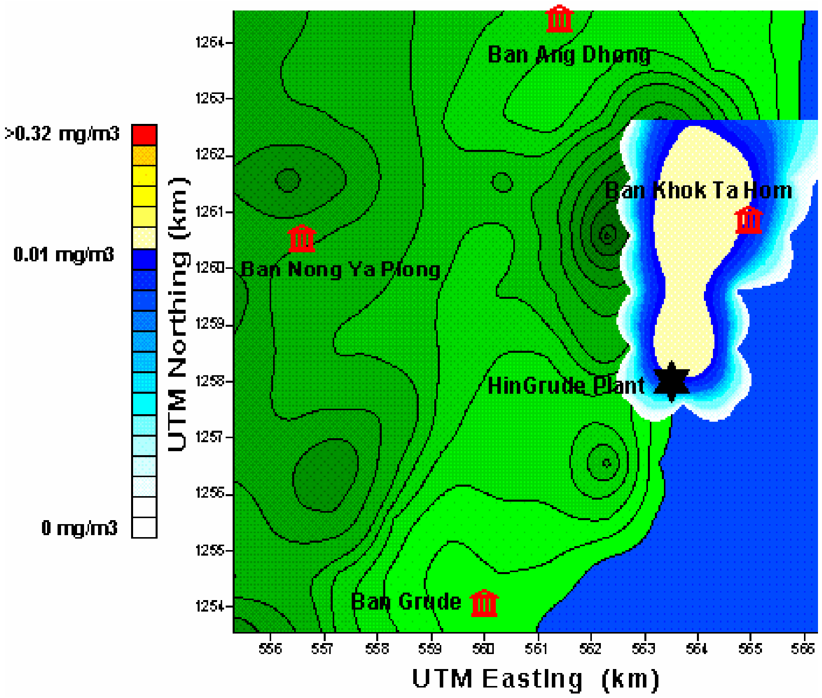
Appendix Figure J29 5th hour dispersion of NO_2 in summer



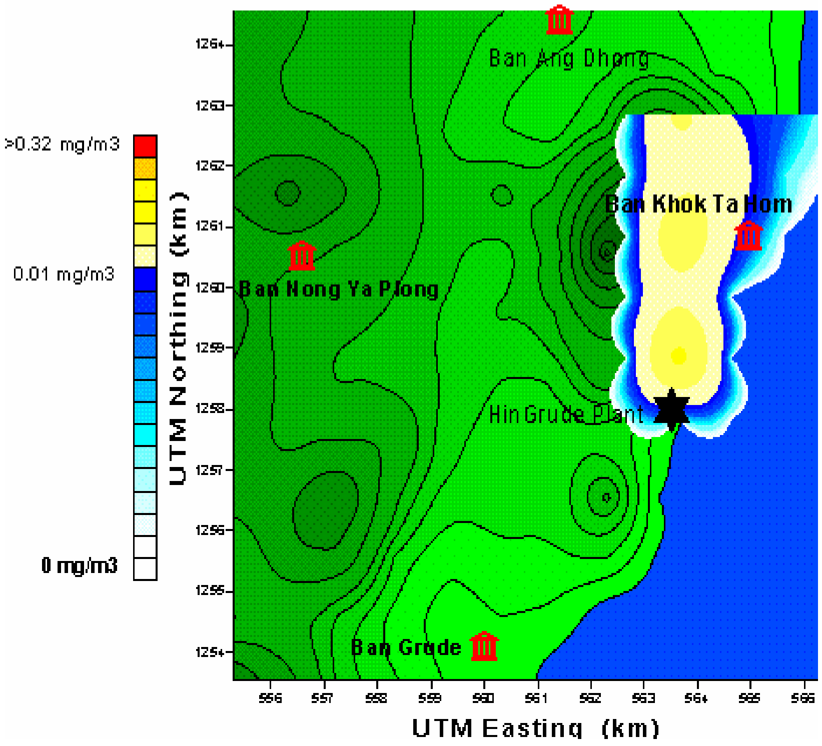
Appendix Figure J30 6th hour dispersion of NO_2 in summer



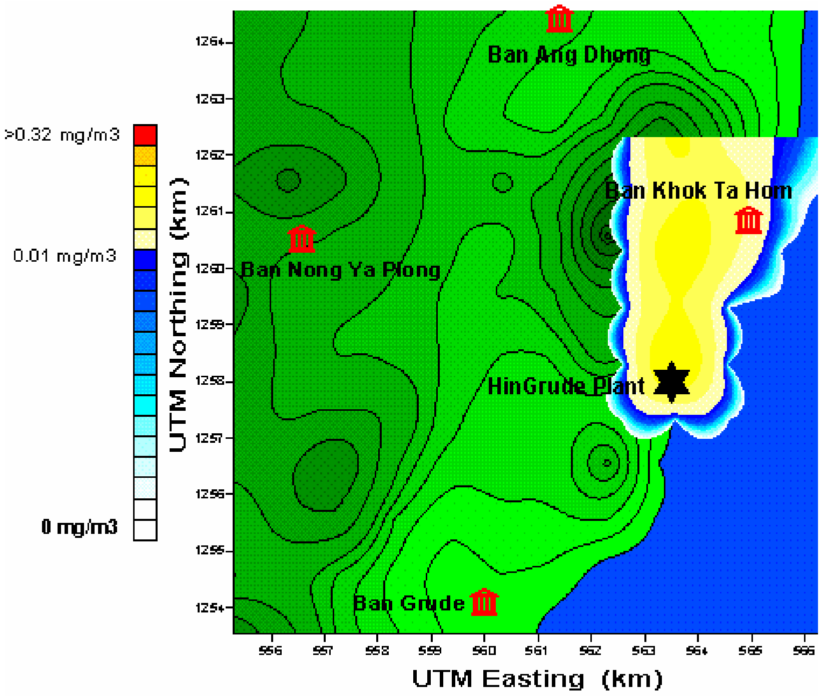
Appendix Figure J31 7th hour dispersion of NO_2 in summer



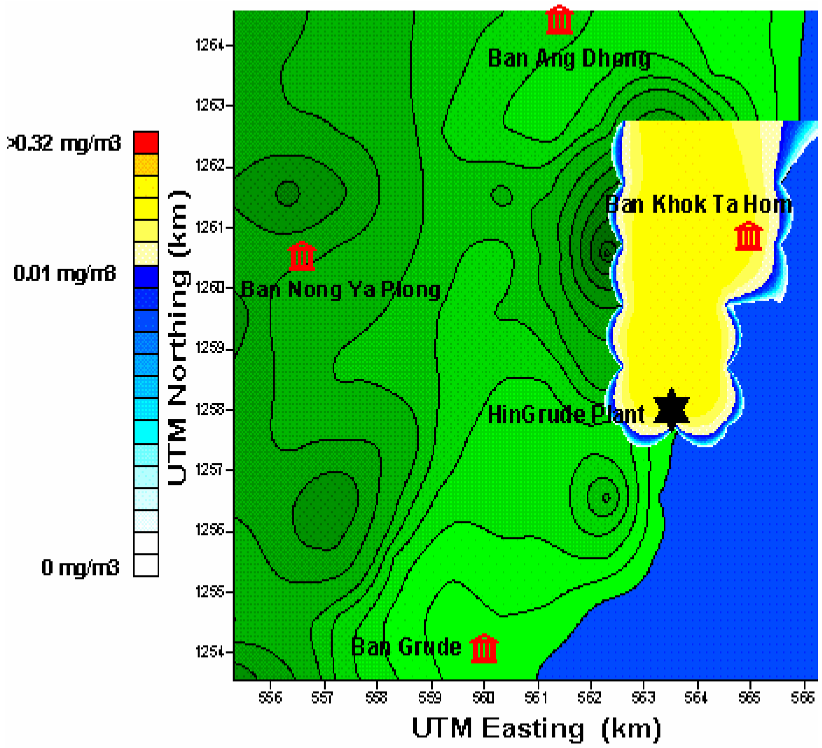
Appendix Figure J32 8th hour dispersion of NO_2 in summer



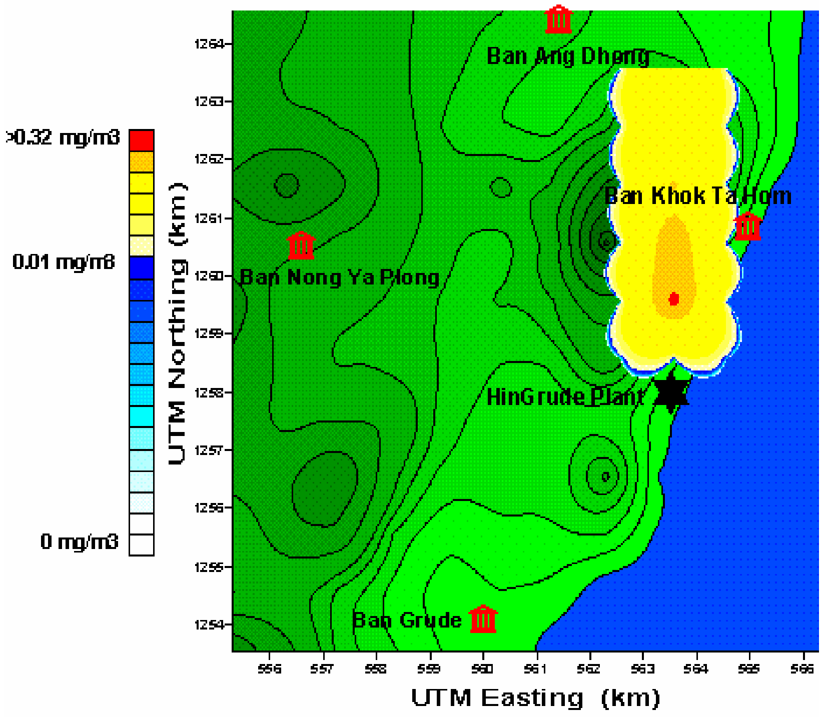
Appendix Figure J33 9th hour dispersion of NO_2 in summer



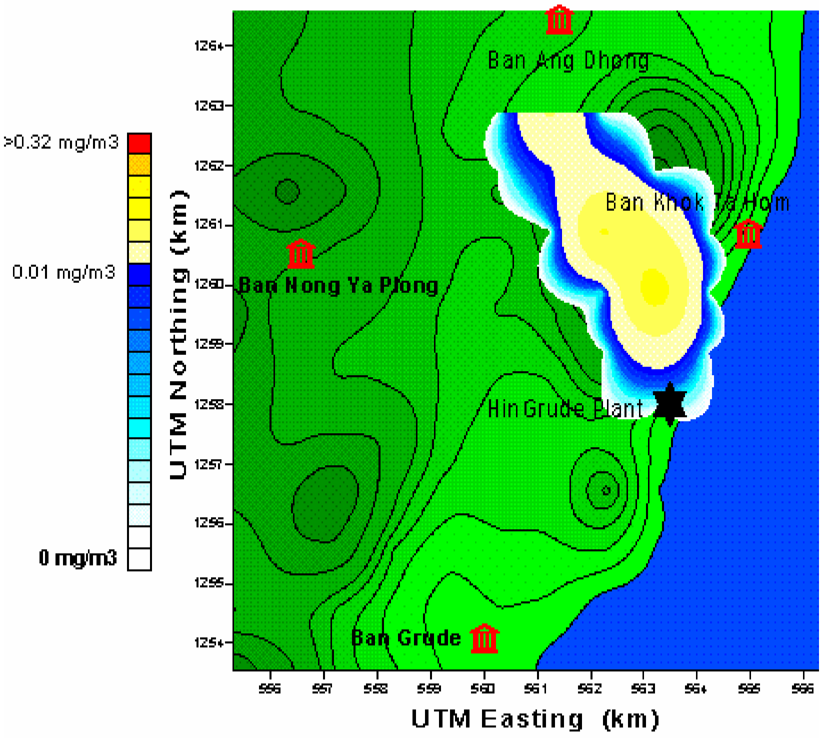
Appendix Figure J34 10th hour dispersion of NO_2 in summer



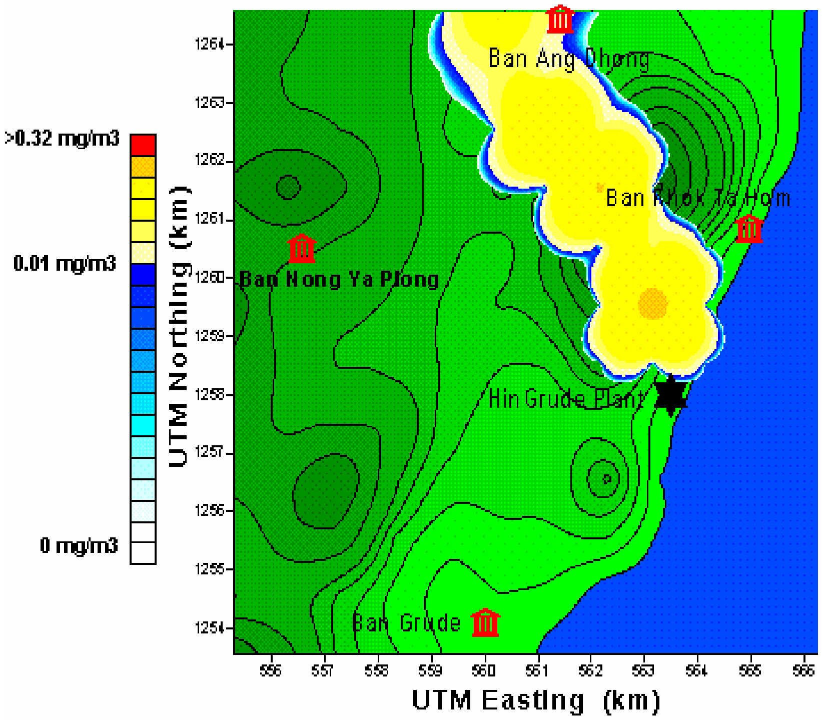
Appendix Figure J35 11th hour dispersion of NO_2 in summer



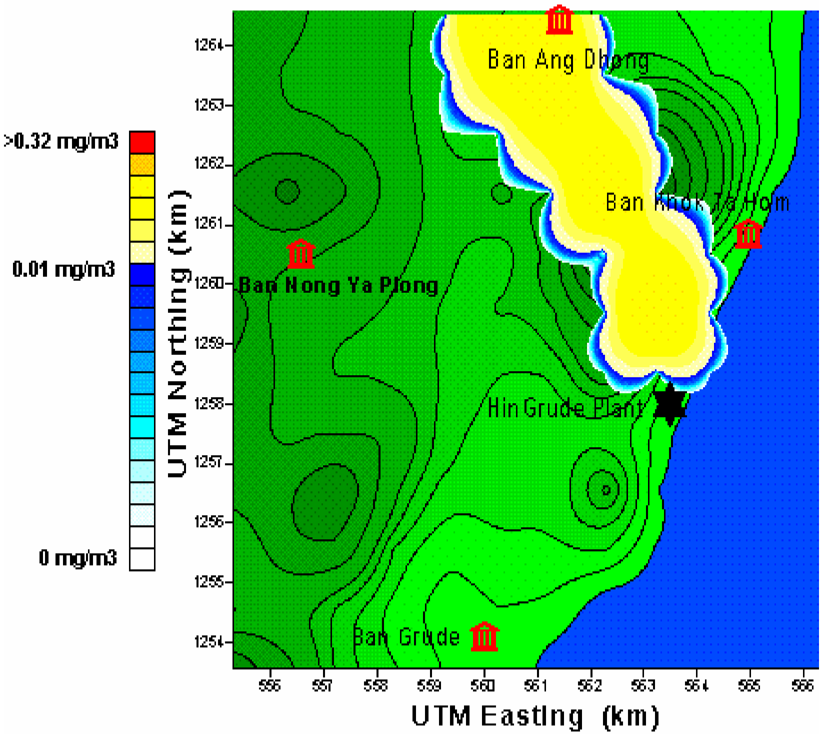
Appendix Figure J36 12th hour dispersion of NO_2 in summer



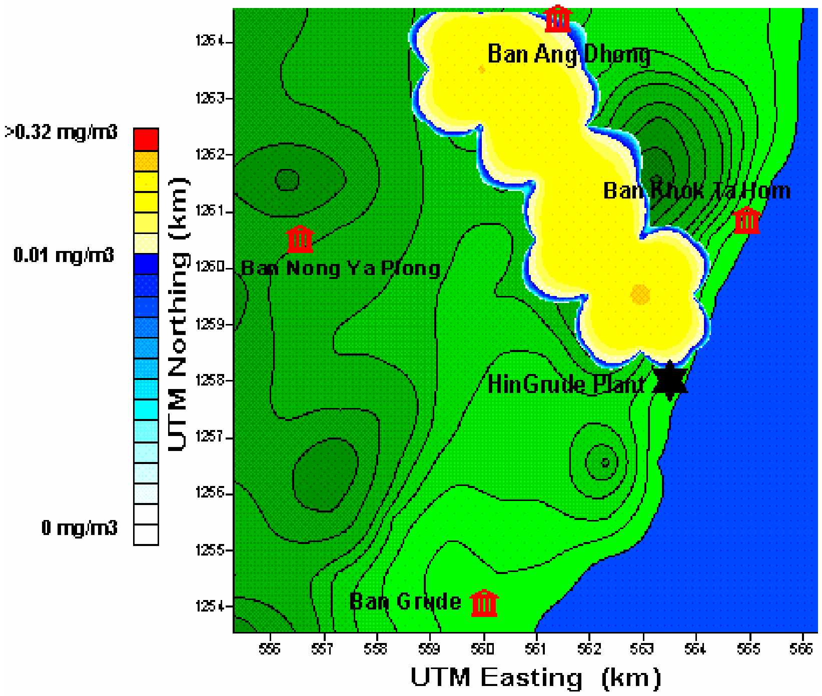
Appendix Figure J37 13th hour dispersion of NO_2 in summer



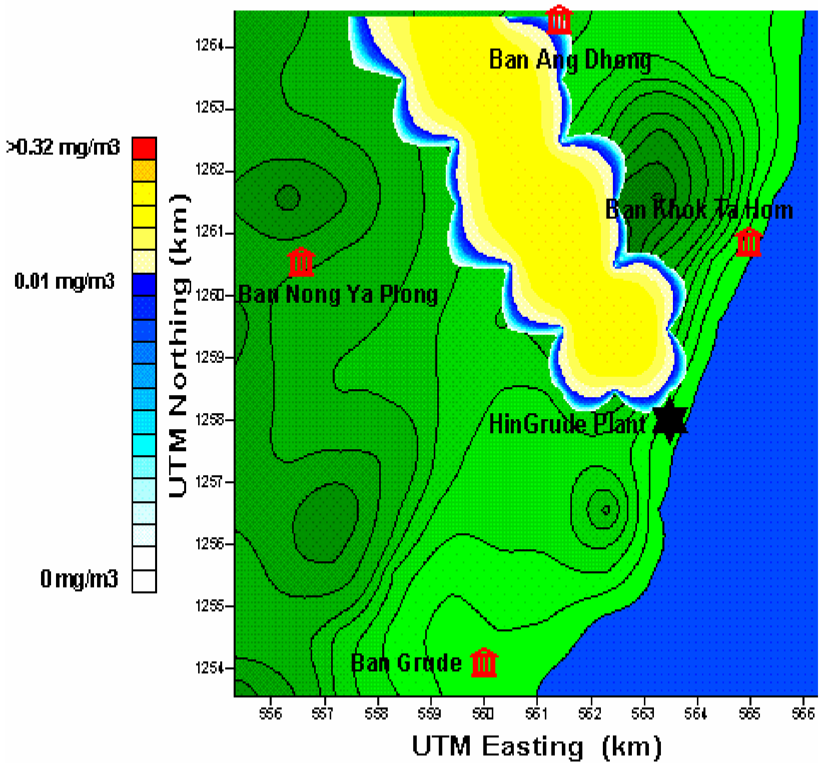
Appendix Figure J38 14th hour dispersion of NO_2 in summer



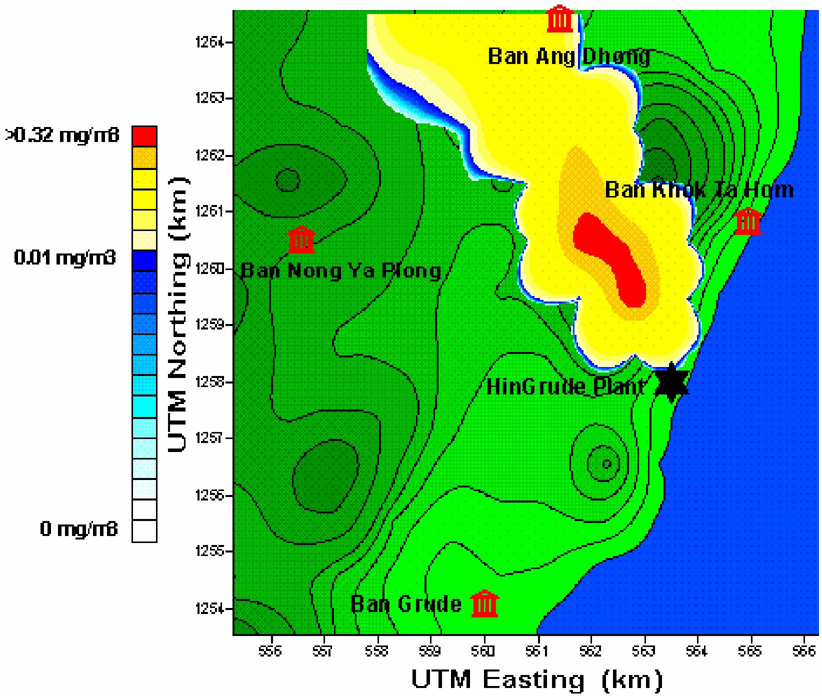
Appendix Figure J39 15th hour dispersion of NO_2 in summer



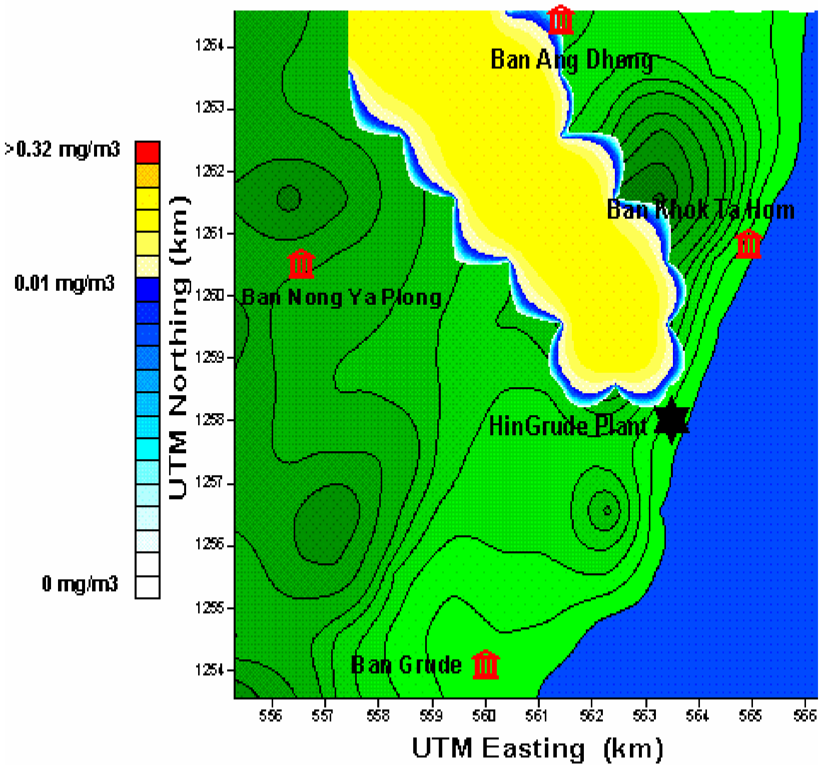
Appendix Figure J40 16th hour dispersion of NO_2 in summer



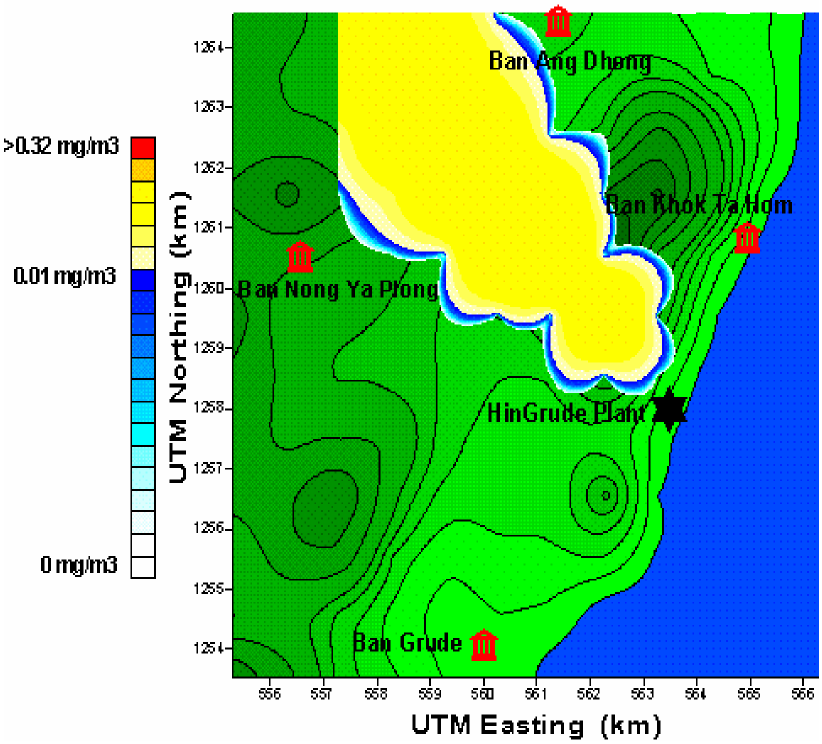
Appendix Figure J41 17th hour dispersion of NO_2 in summer



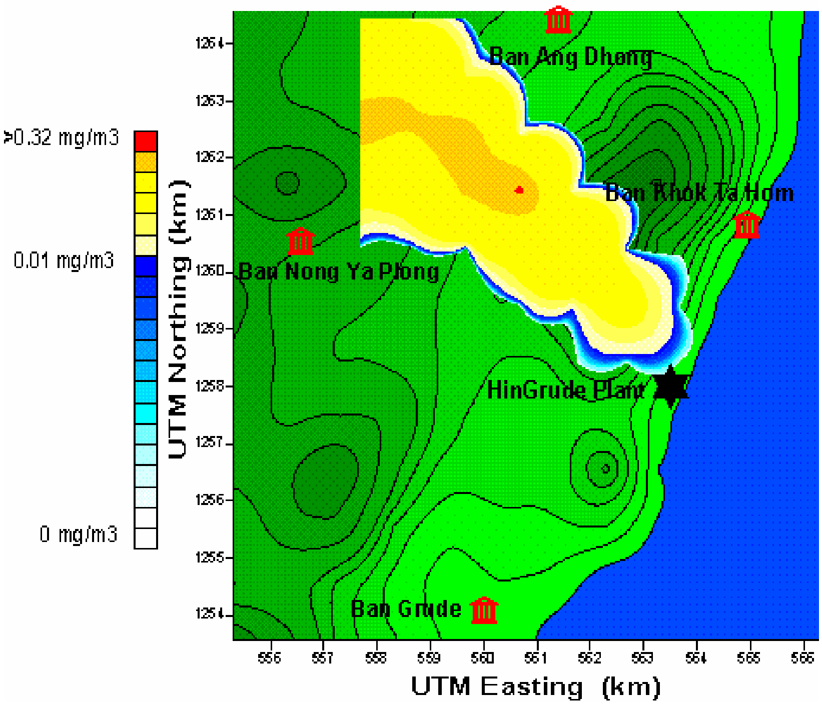
Appendix Figure J42 18th hour dispersion of NO_2 in summer



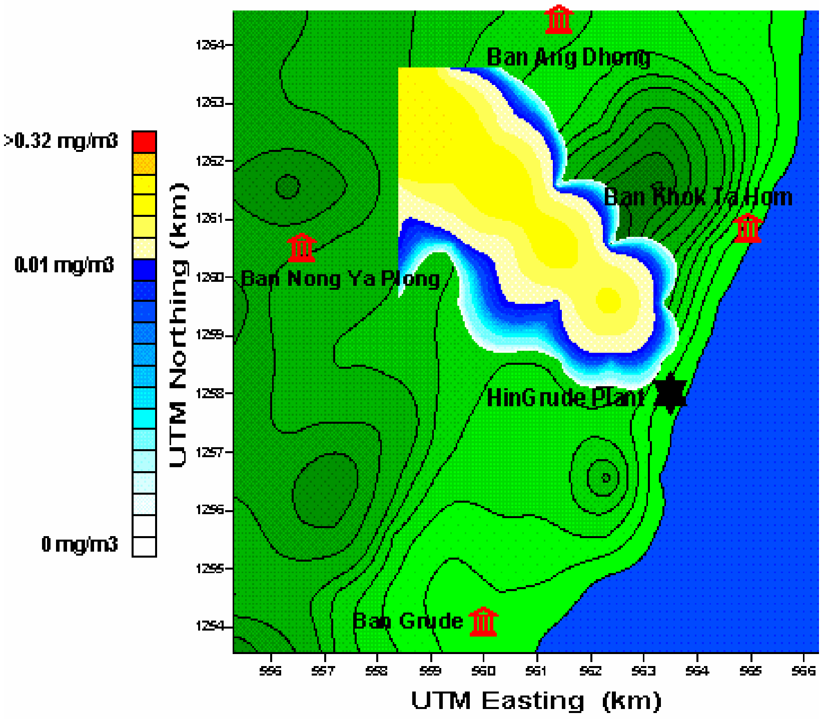
Appendix Figure J43 19th hour dispersion of NO_2 in summer



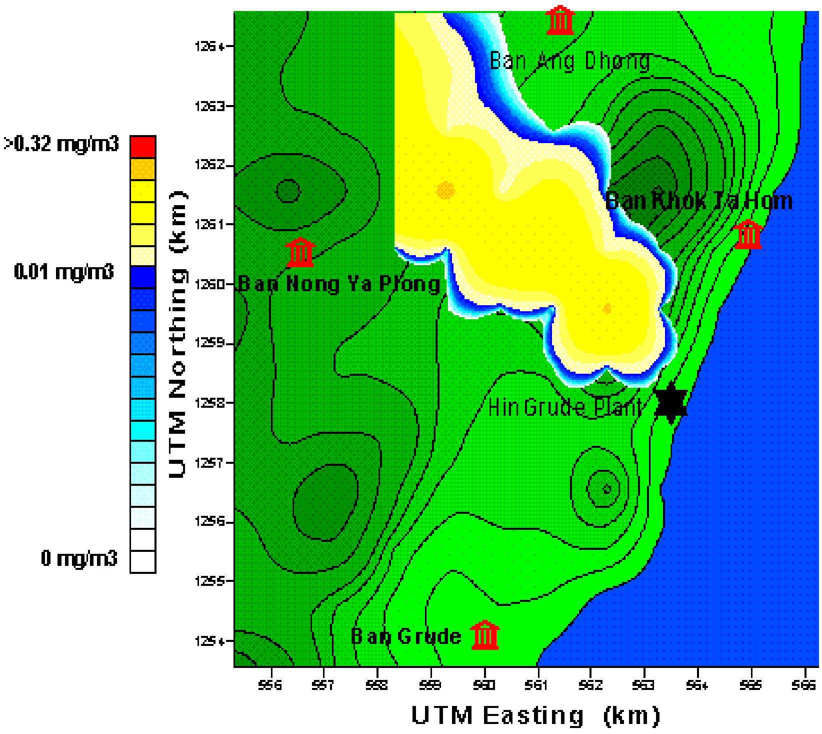
Appendix Figure J44 20th hour dispersion of NO_2 in summer



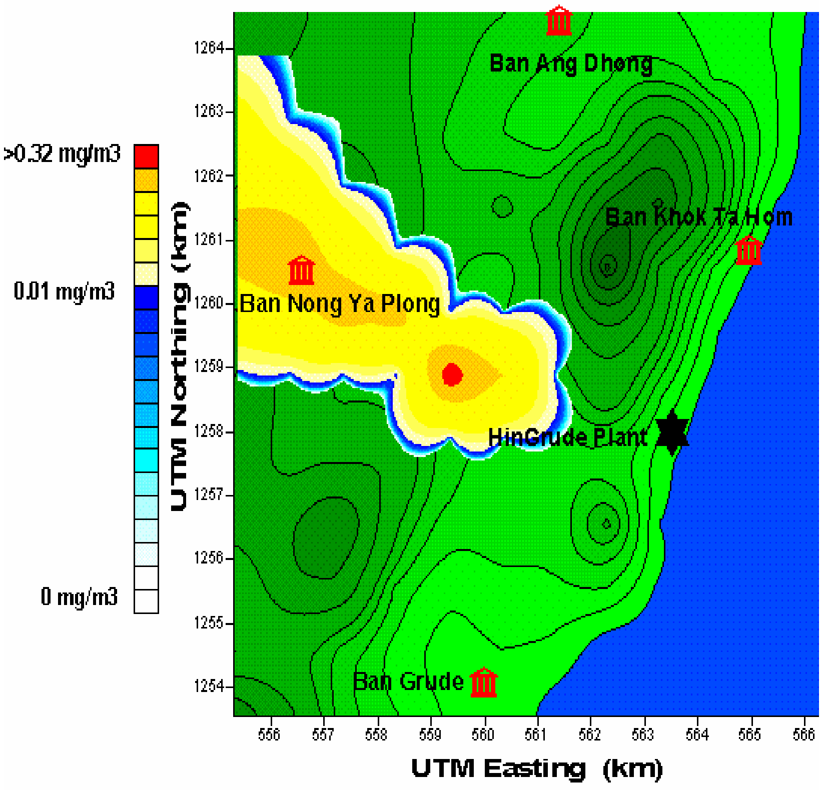
Appendix Figure J45 21st hour dispersion of NO_2 in summer



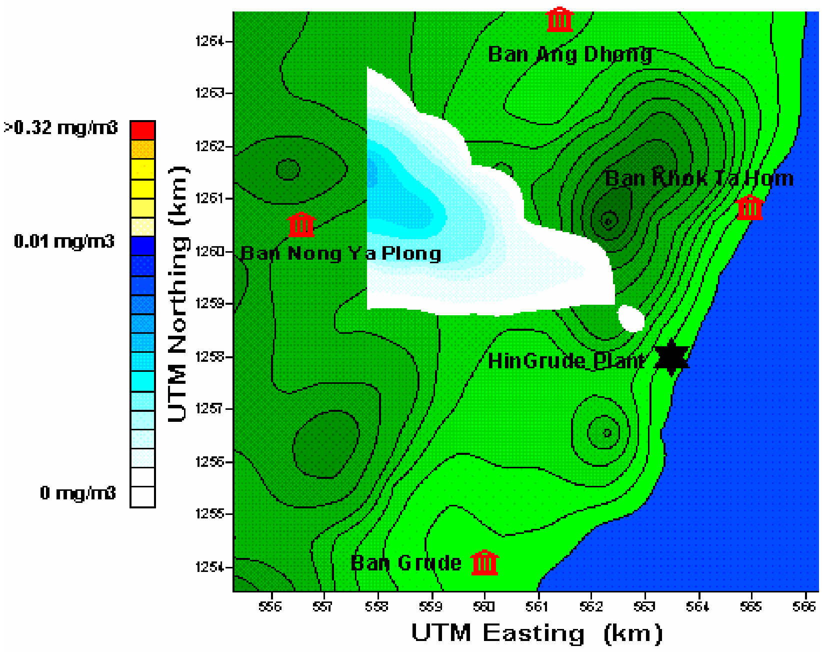
Appendix Figure J46 22nd hour dispersion of NO_2 in summer



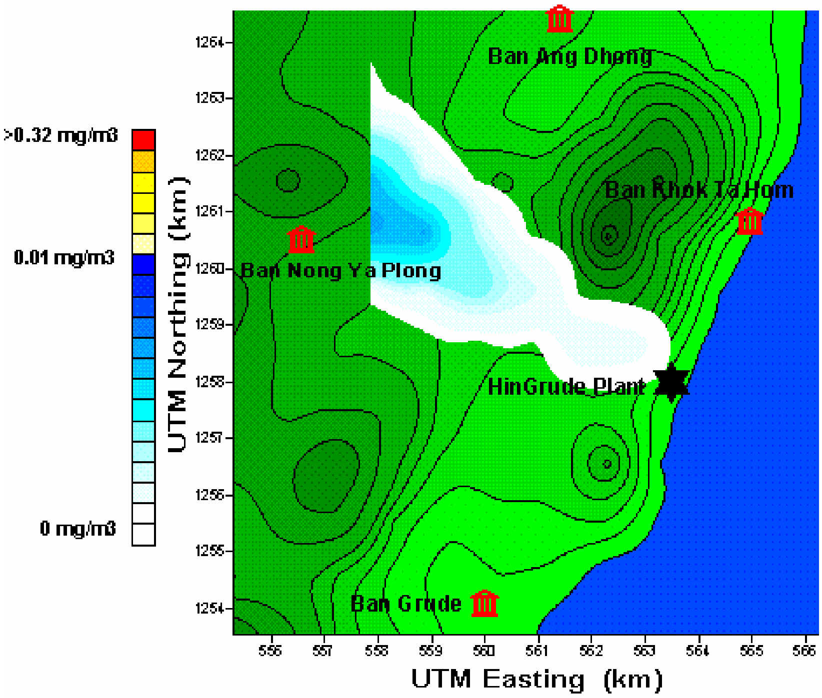
Appendix Figure J47 23rd hour dispersion of NO_2 in summer



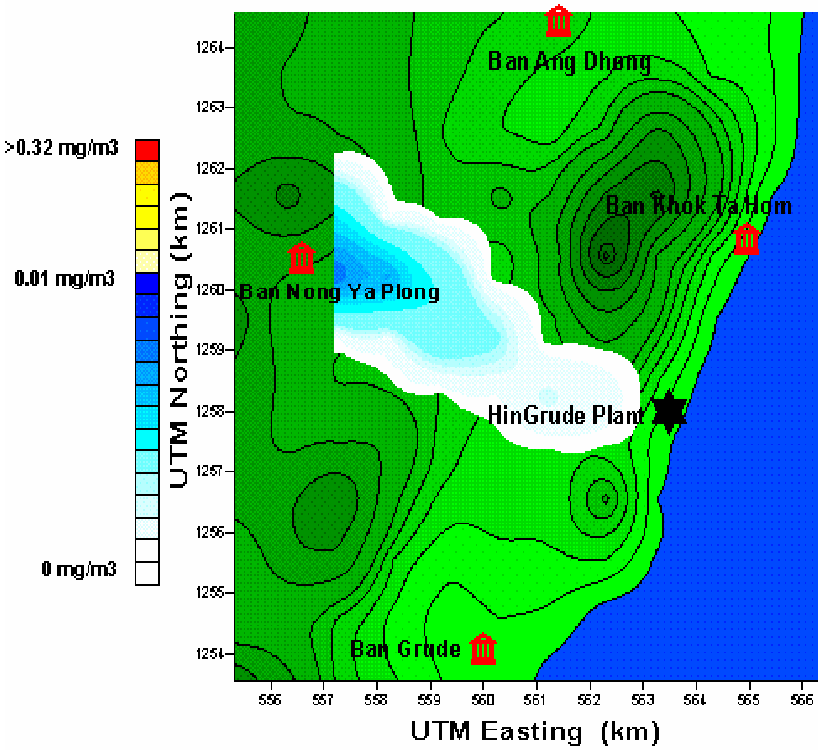
Appendix Figure J48 24th hour dispersion of NO_2 in summer



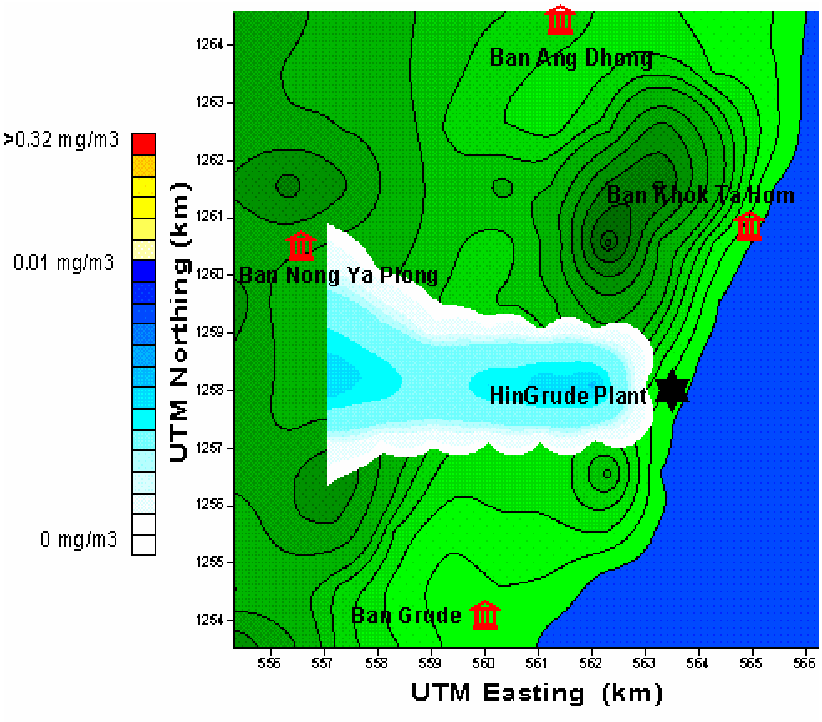
Appendix Figure J49 1st hour dispersion of NO_2 in rainy season



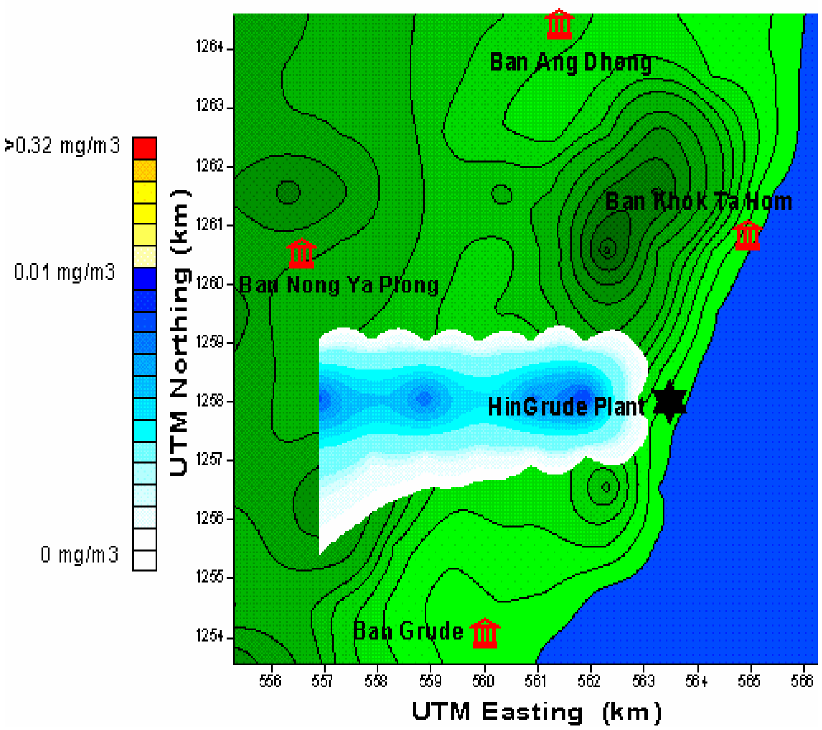
Appendix Figure J50 2nd hour dispersion of NO_2 in rainy season



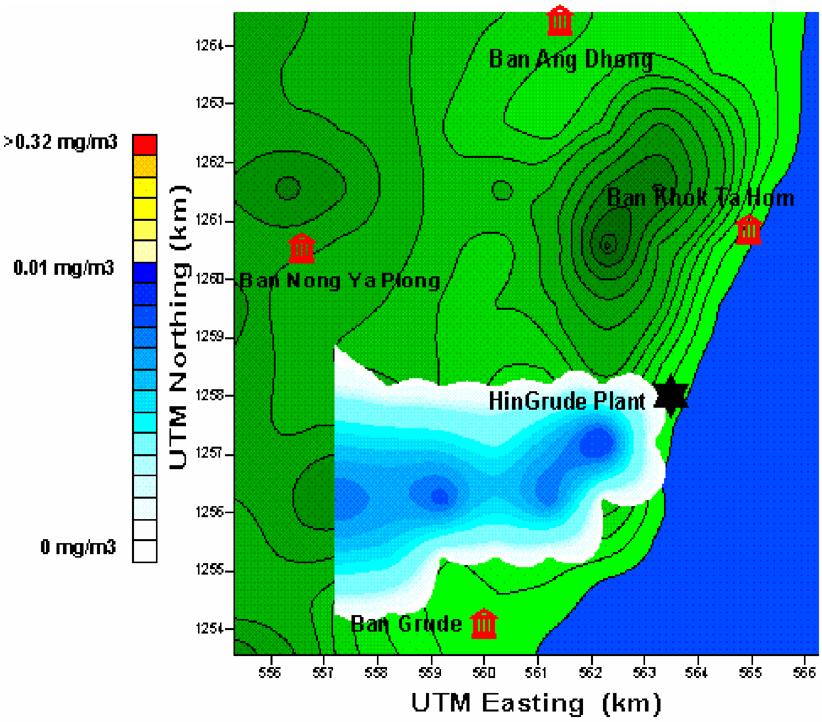
Appendix Figure J51 3rd hour dispersion of NO_2 in rainy season



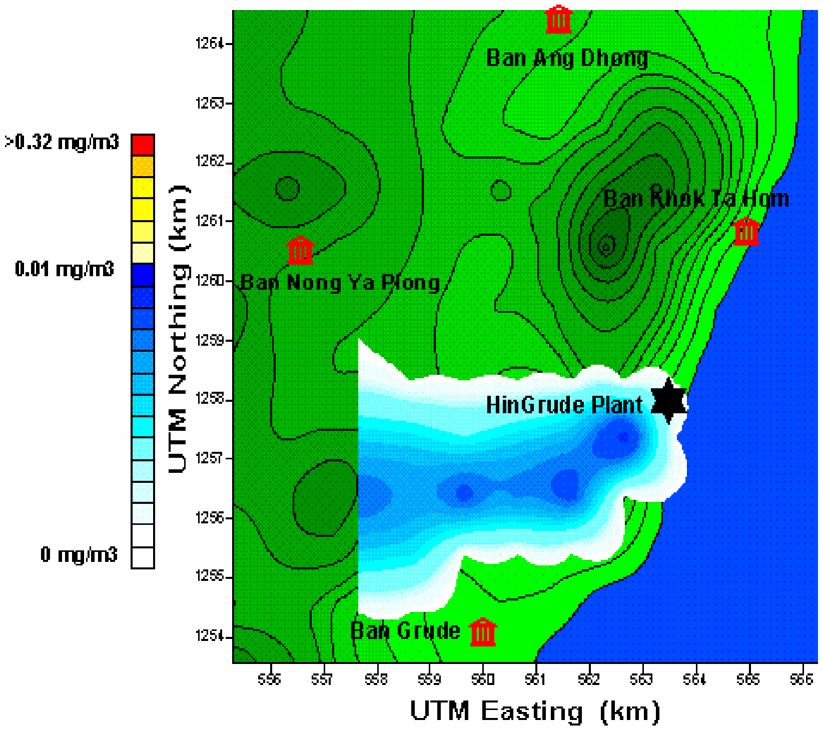
Appendix Figure J52 4th hour dispersion of NO_2 in rainy season



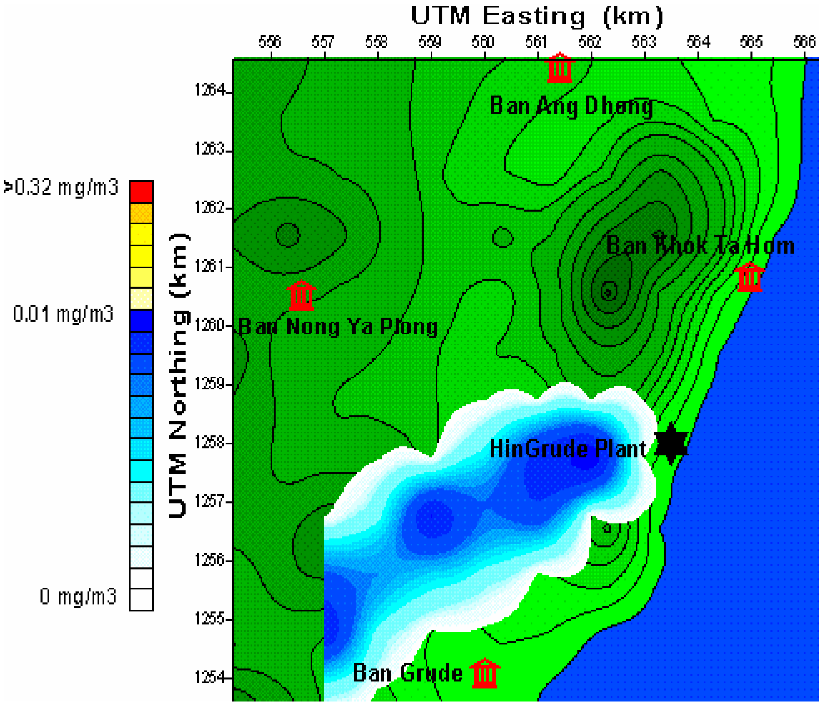
Appendix Figure J53 5th hour dispersion of NO_2 in rainy season



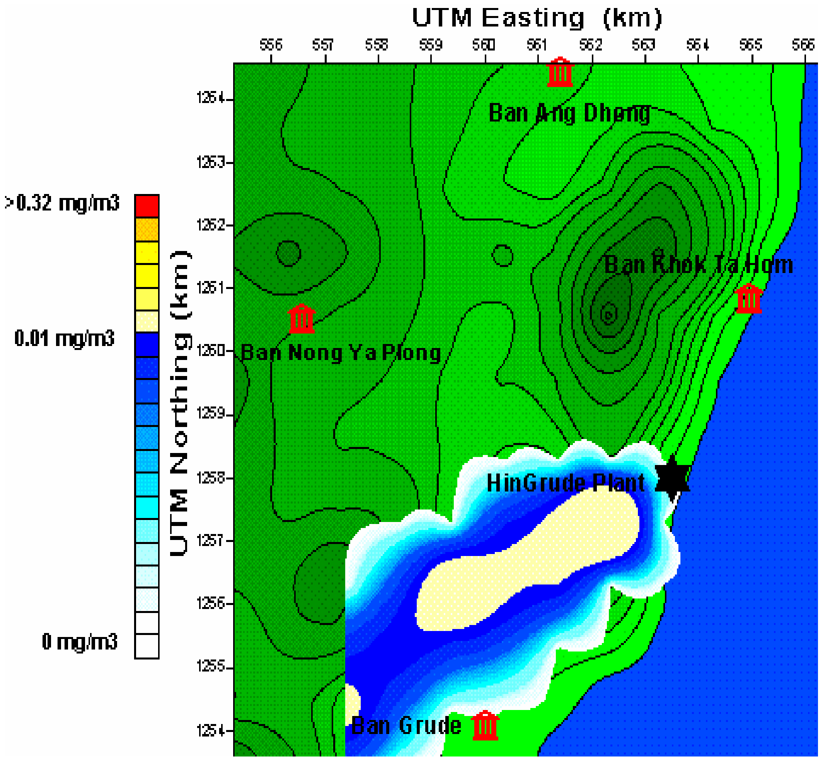
Appendix Figure J54 6th hour dispersion of NO_2 in rainy season



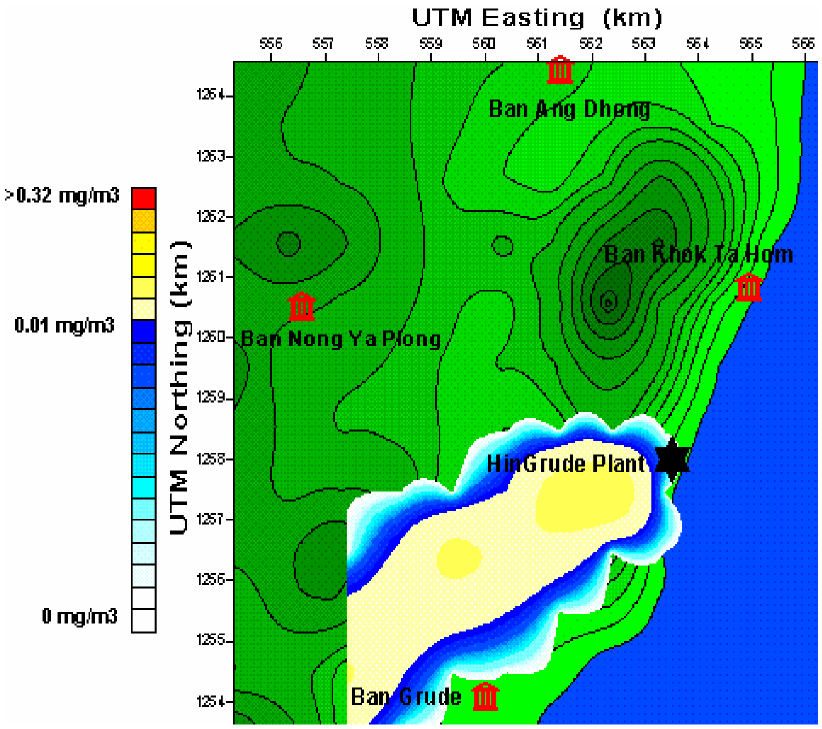
Appendix Figure J55 7th hour dispersion of NO_2 in rainy season



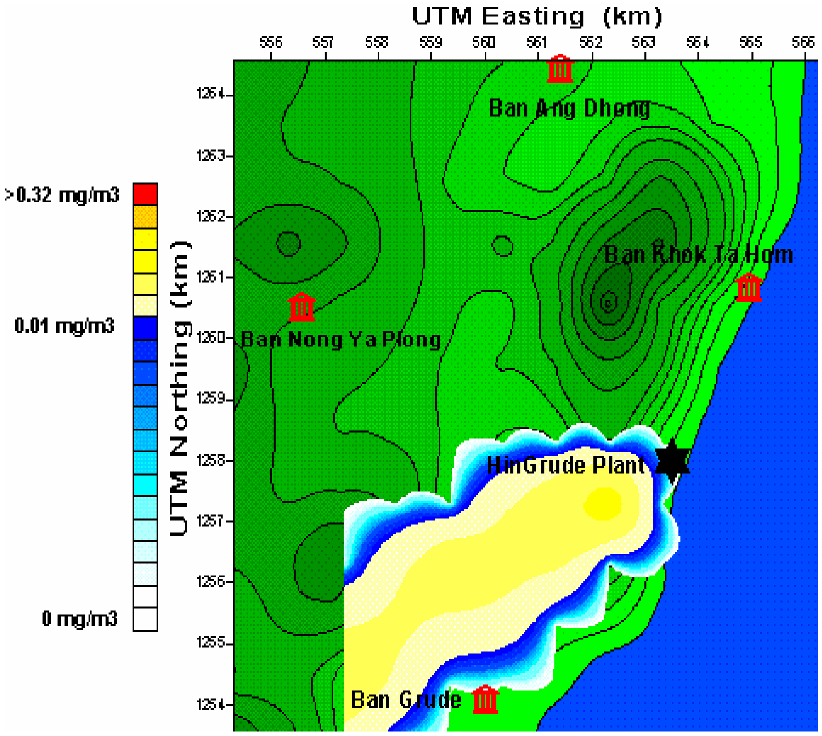
Appendix Figure J56 8th hour dispersion of NO_2 in rainy season



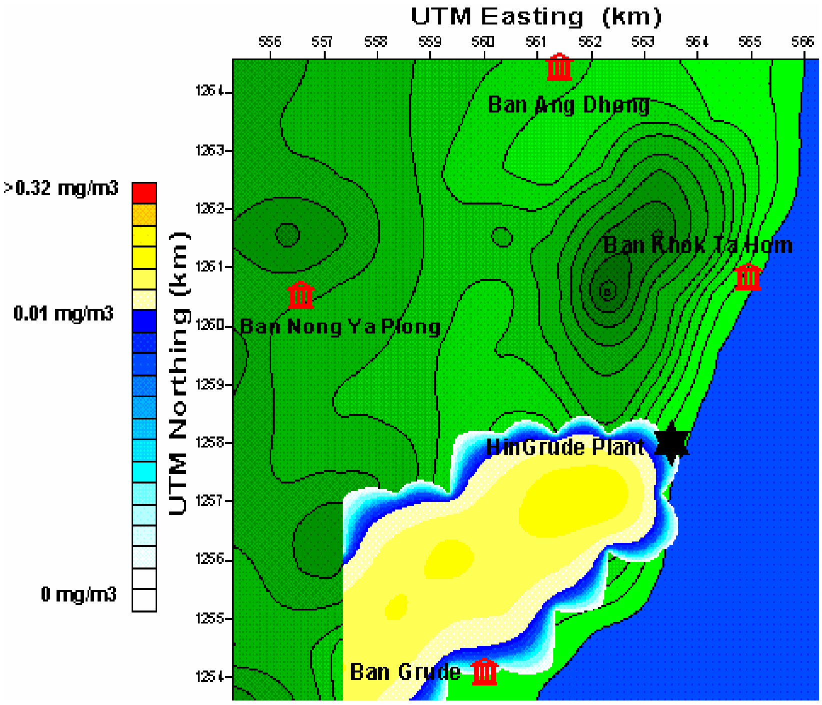
Appendix Figure J57 9th hour dispersion of NO_2 in rainy season



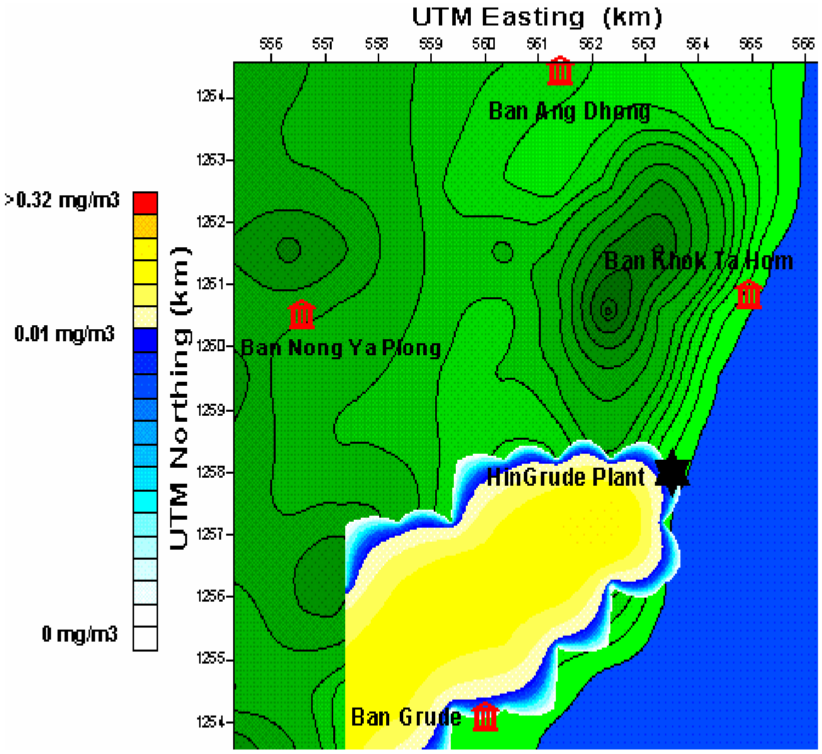
Appendix Figure J58 10th hour dispersion of NO_2 in rainy season



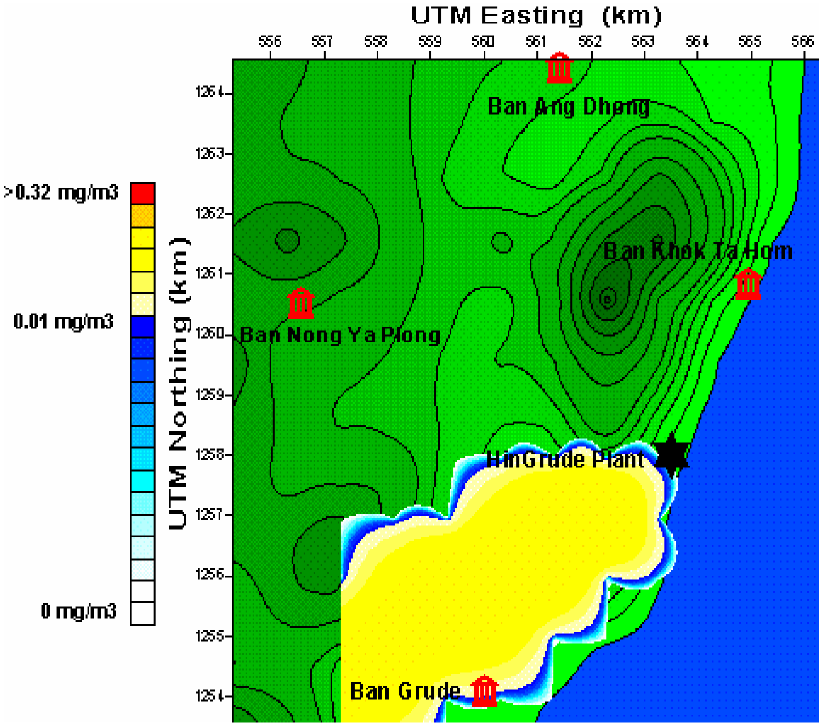
Appendix Figure J59 11th hour dispersion of NO_2 in rainy season



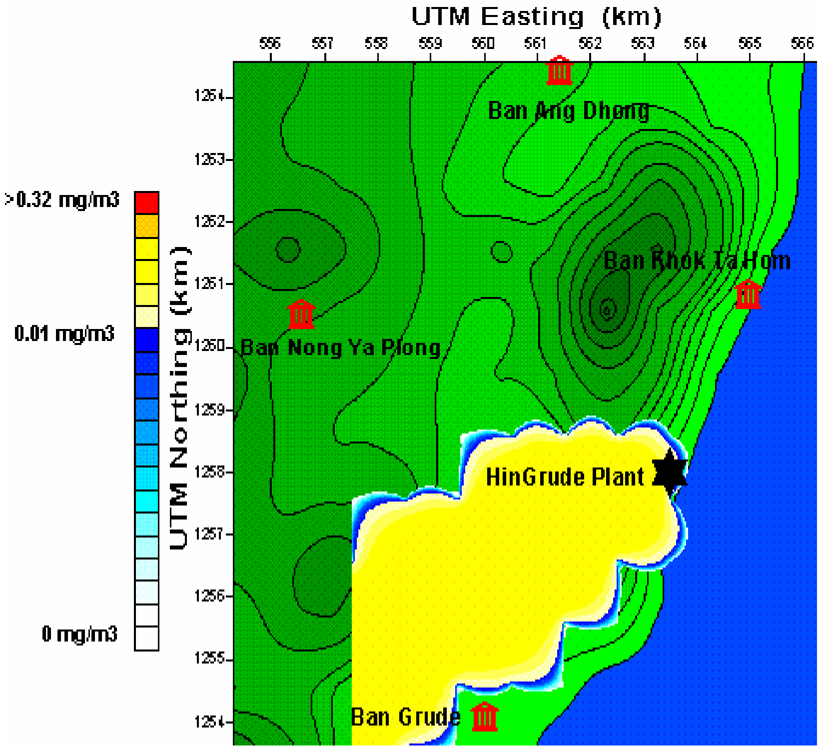
Appendix Figure J60 12th hour dispersion of NO_2 in rainy season



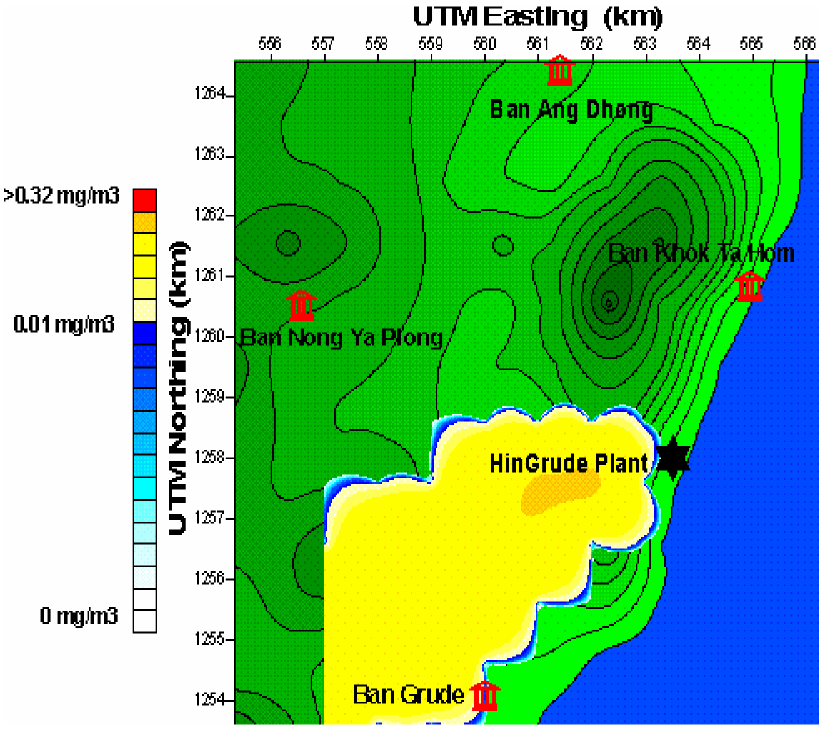
Appendix Figure J61 13th hour dispersion of NO_2 in rainy season



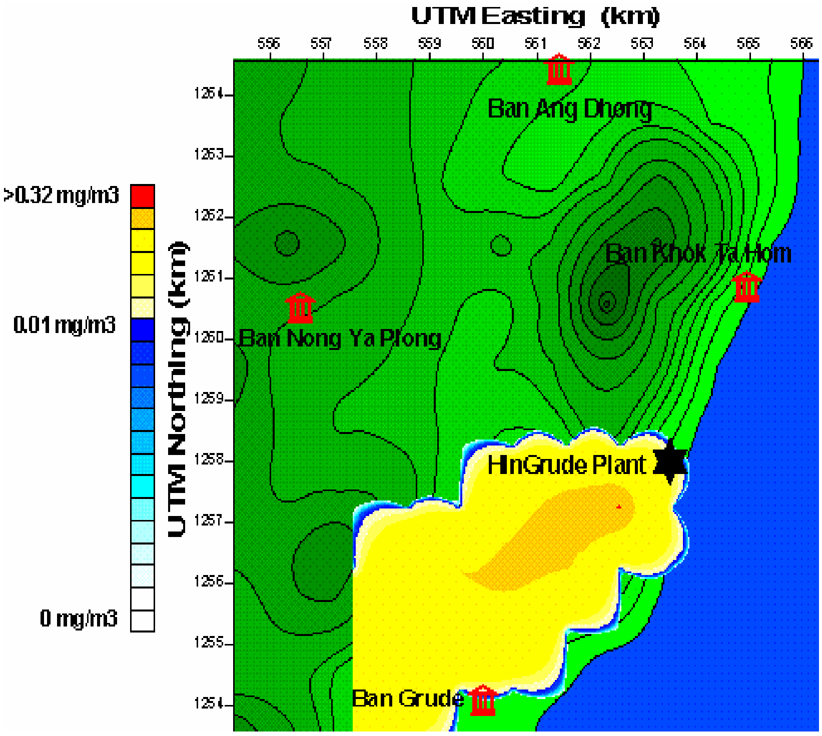
Appendix Figure J62 14th hour dispersion of NO_2 in rainy season



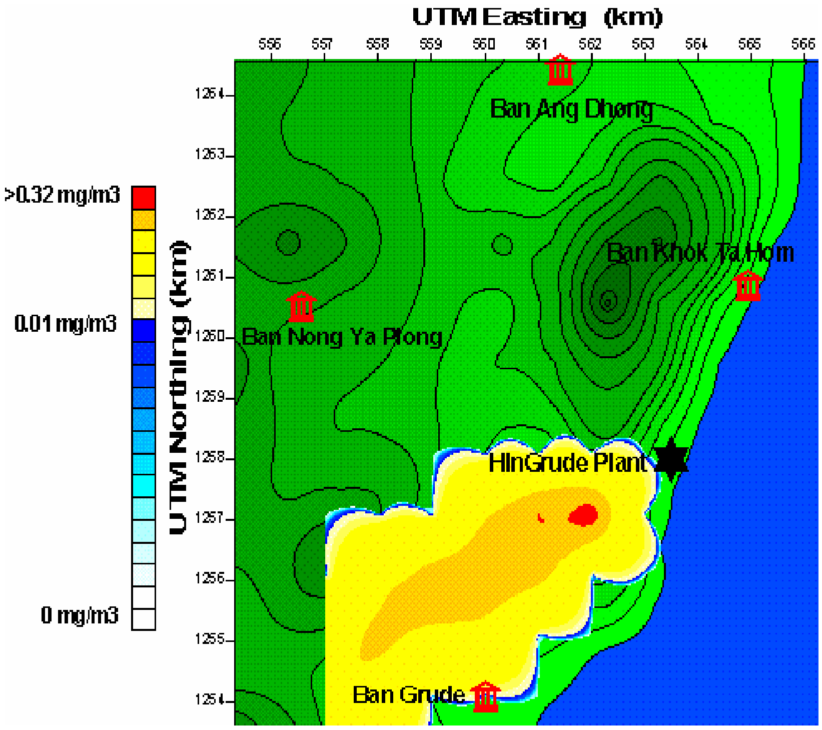
Appendix Figure J63 15th hour dispersion of NO_2 in rainy season



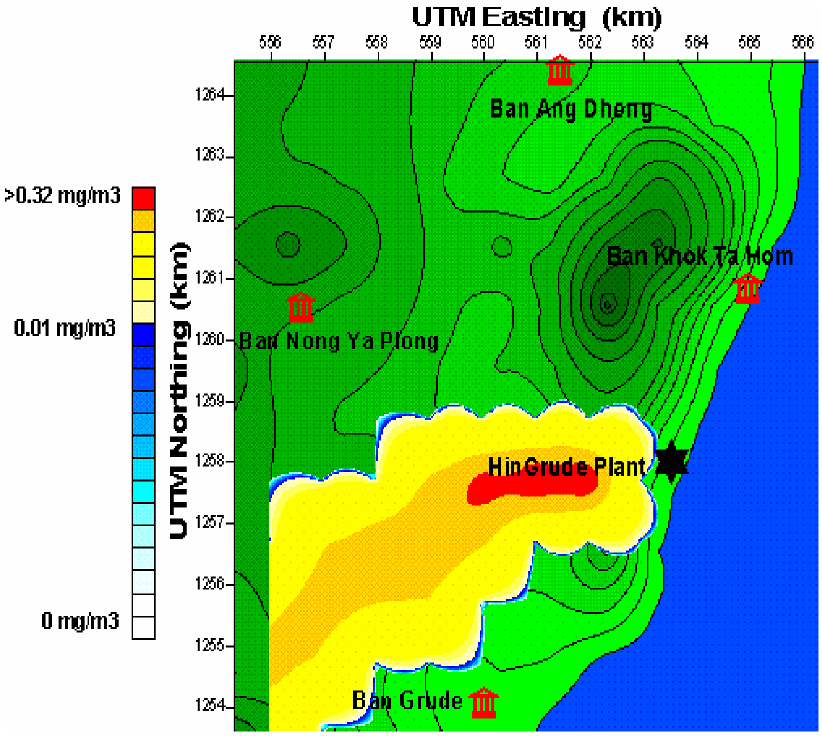
Appendix Figure J64 16th hour dispersion of NO_2 in rainy season



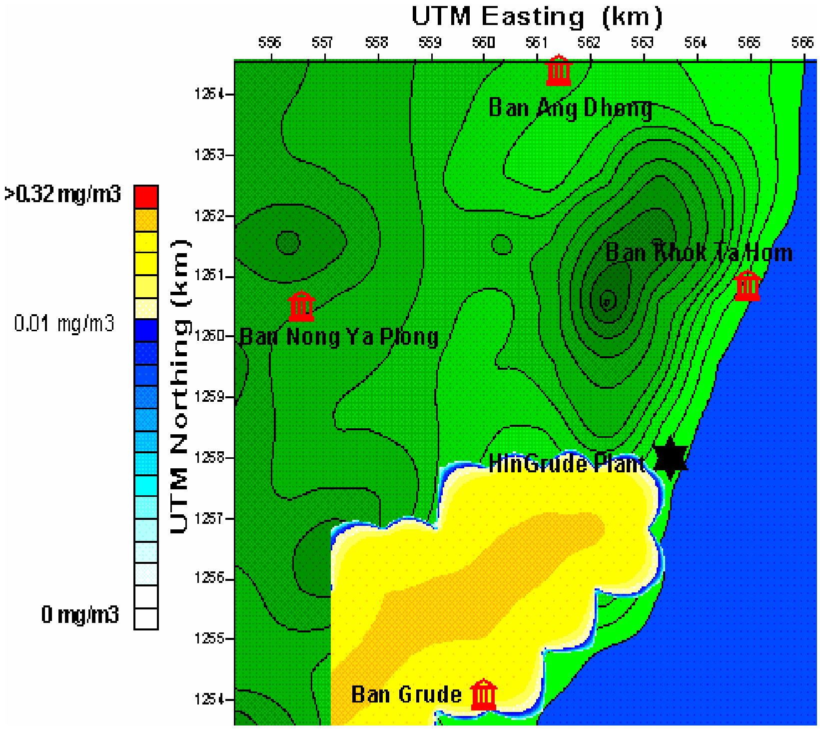
Appendix Figure J65 17th hour dispersion of NO_2 in rainy season



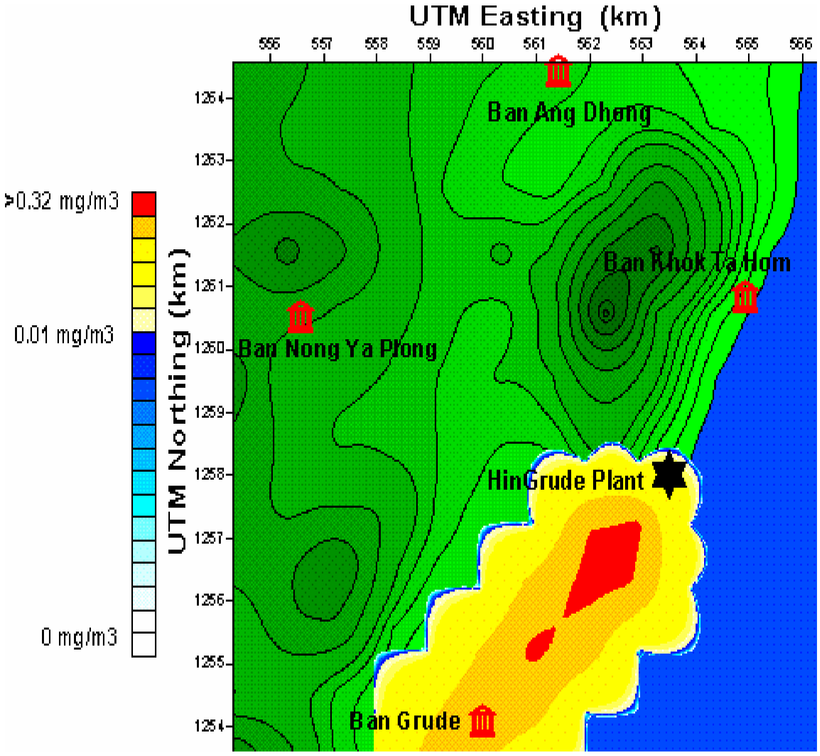
Appendix Figure J66 18th hour dispersion of NO_2 in rainy season



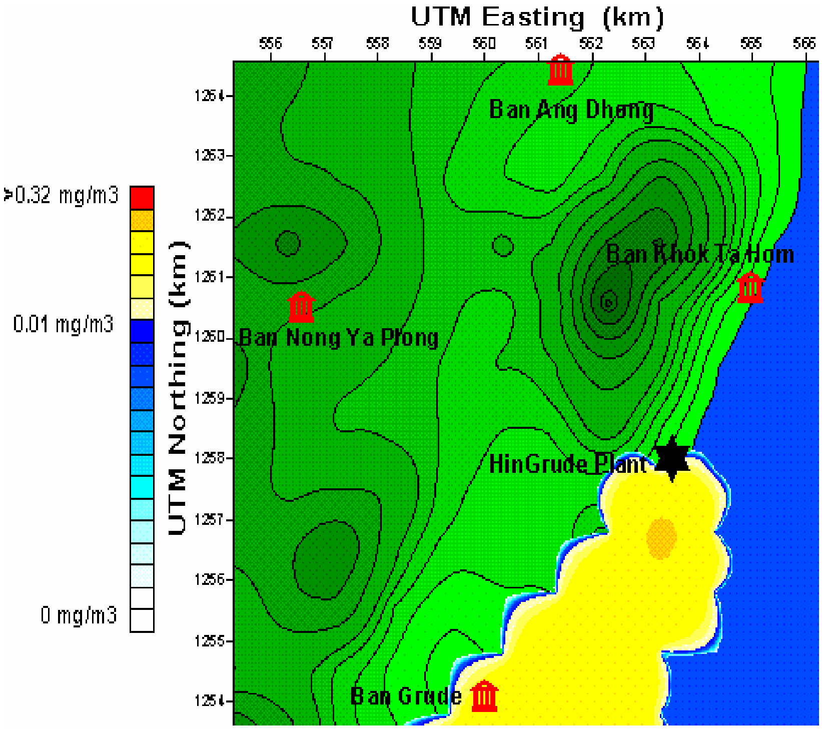
Appendix Figure J67 19th hour dispersion of NO_2 in rainy season



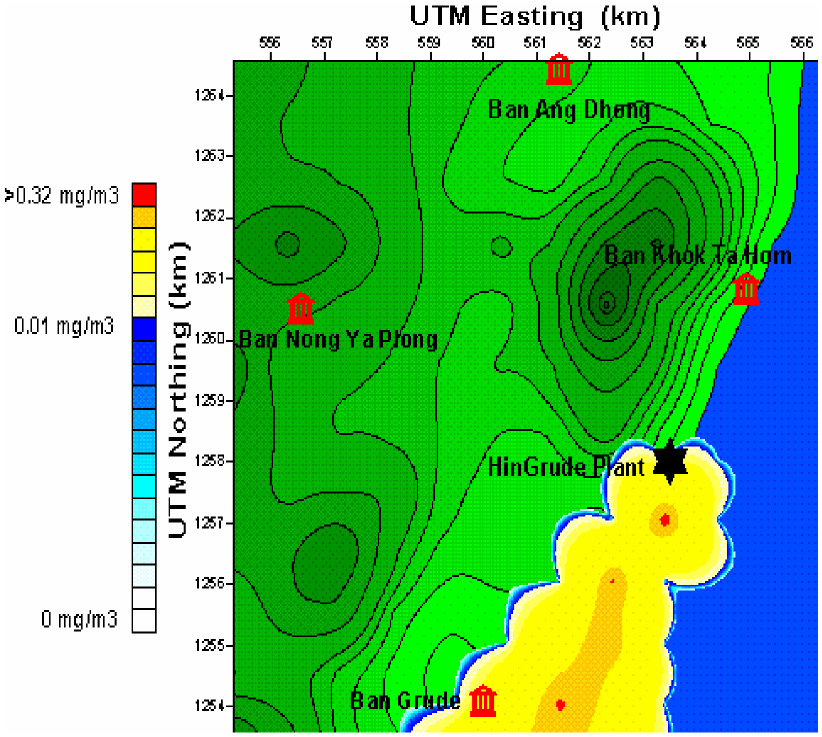
Appendix Figure J68 20th hour dispersion of NO_2 in rainy season



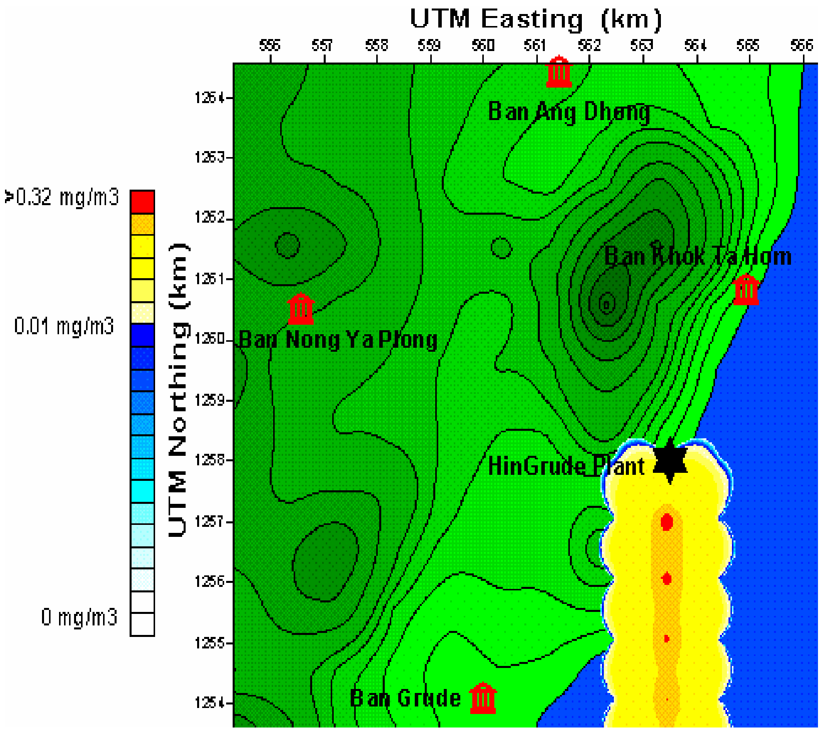
Appendix Figure J69 21st hour dispersion of NO_2 in rainy season



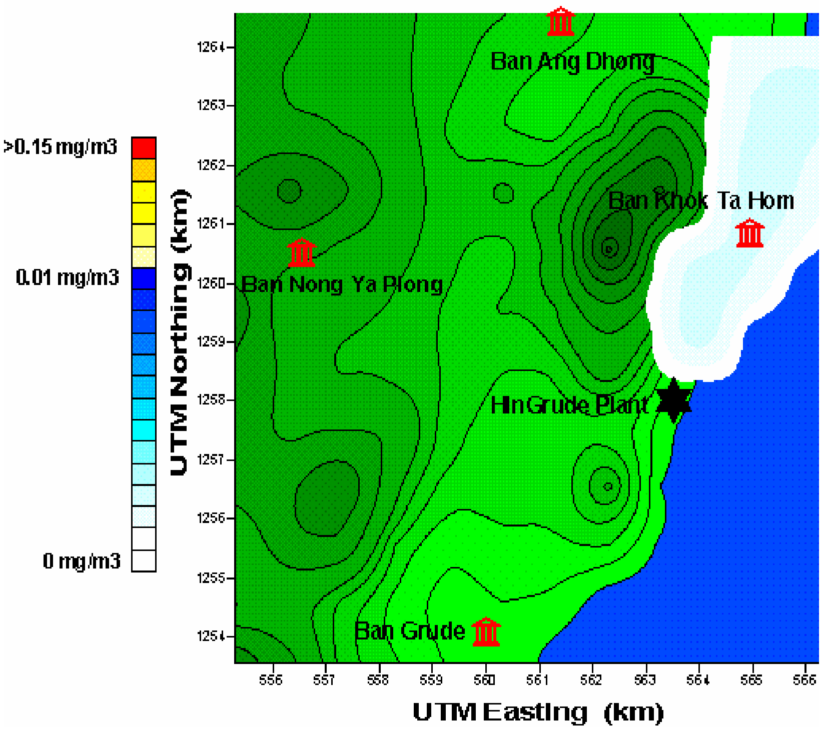
Appendix Figure J70 22nd hour dispersion of NO_2 in rainy season



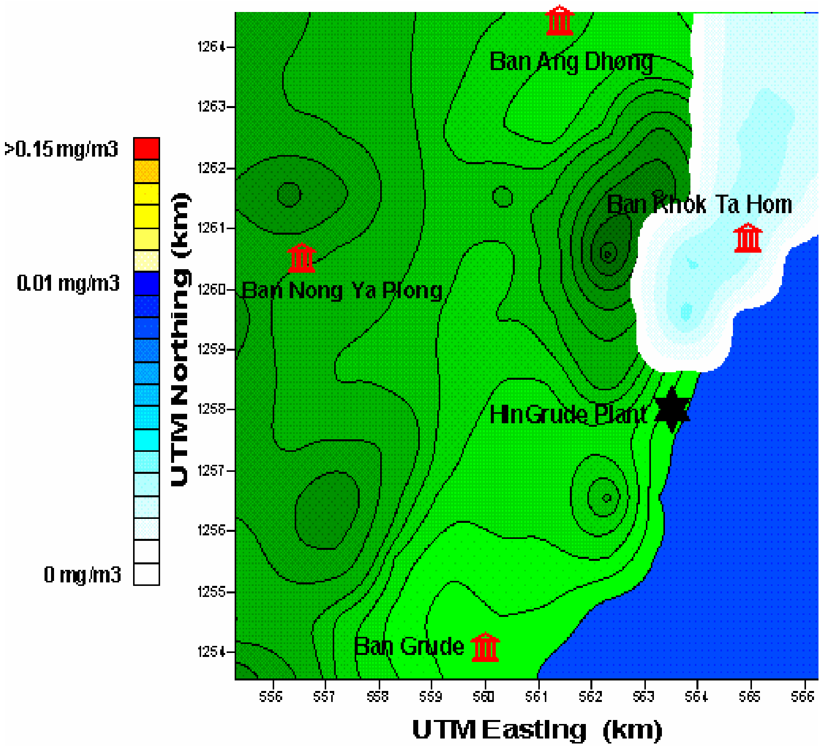
Appendix Figure J71 23rd hour dispersion of NO_2 in rainy season



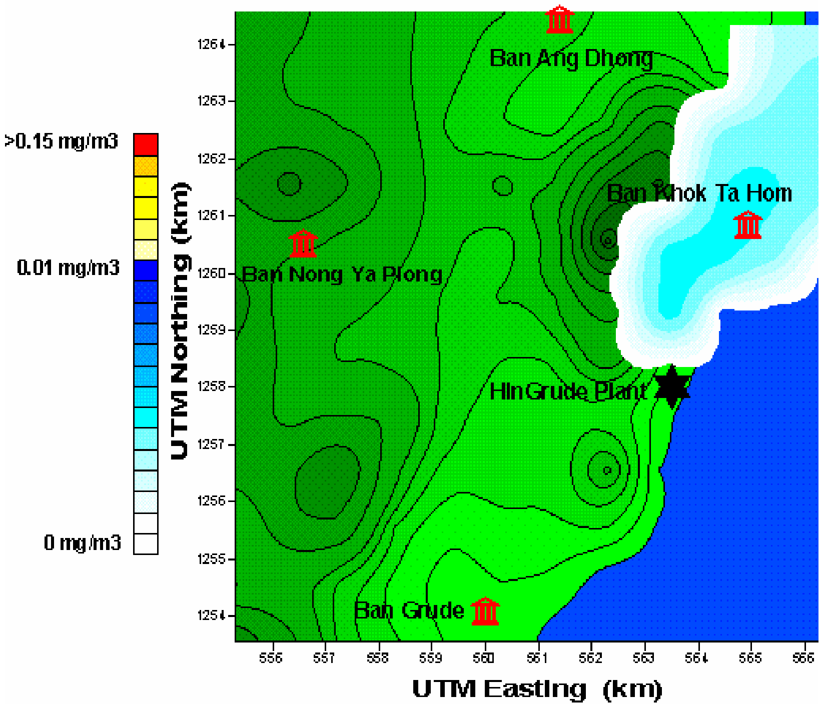
Appendix Figure J72 24th hour dispersion of NO_2 in rainy season



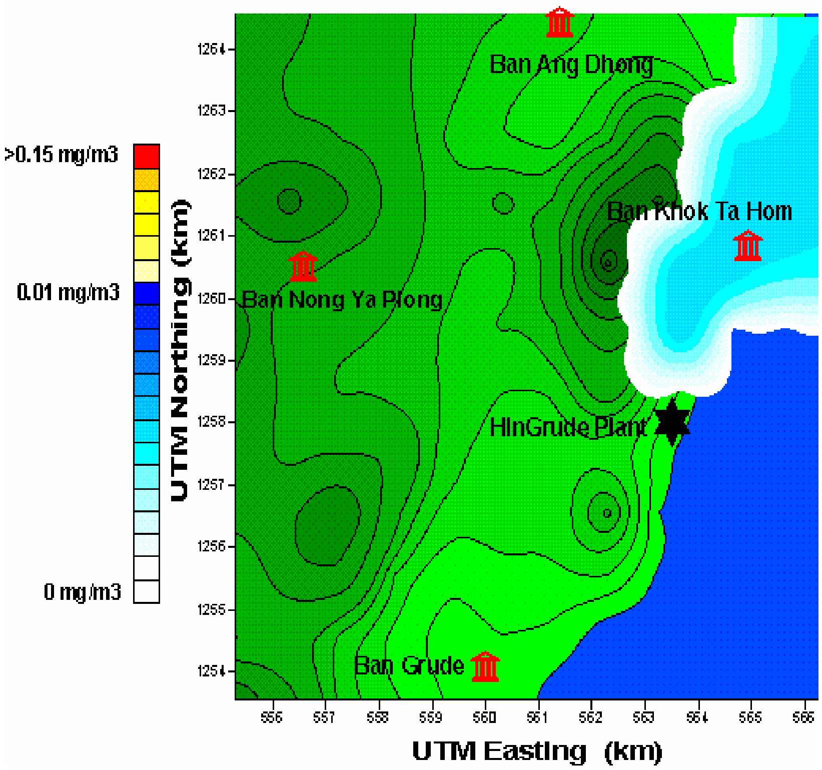
Appendix Figure J73 1st hour dispersion of PM_{10} in winter



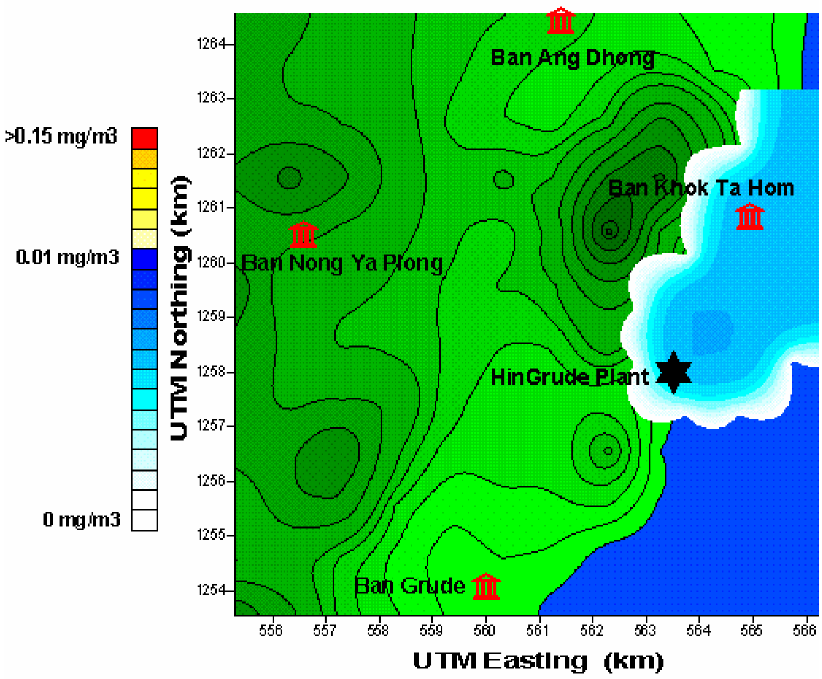
Appendix Figure J74 2nd hour dispersion of PM_{10} in winter



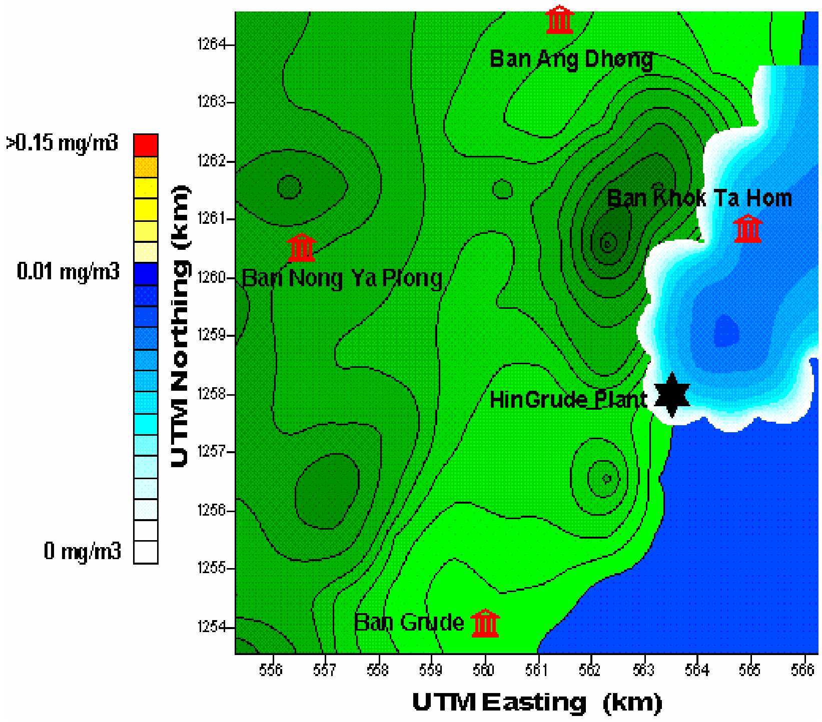
Appendix Figure J75 3rd hour dispersion of PM_{10} in winter



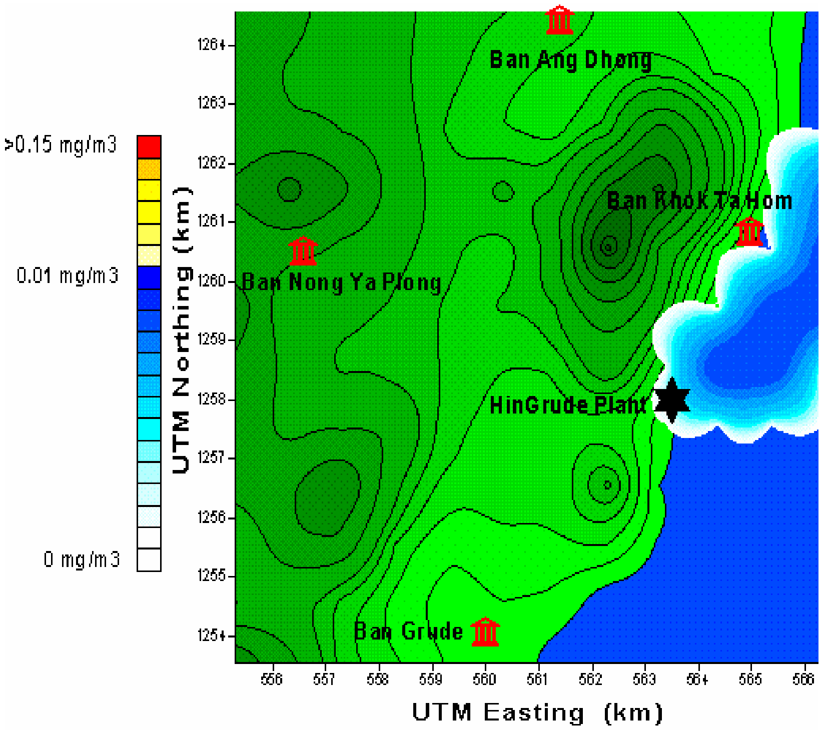
Appendix Figure J76 4th hour dispersion of PM_{10} in winter



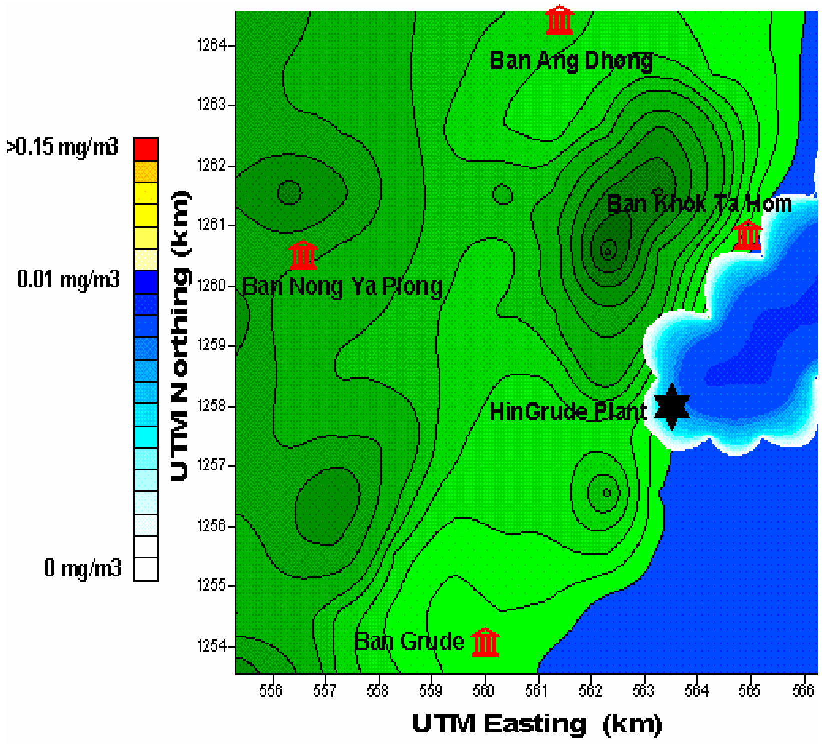
Appendix Figure J77 5th hour dispersion of PM_{10} in winter



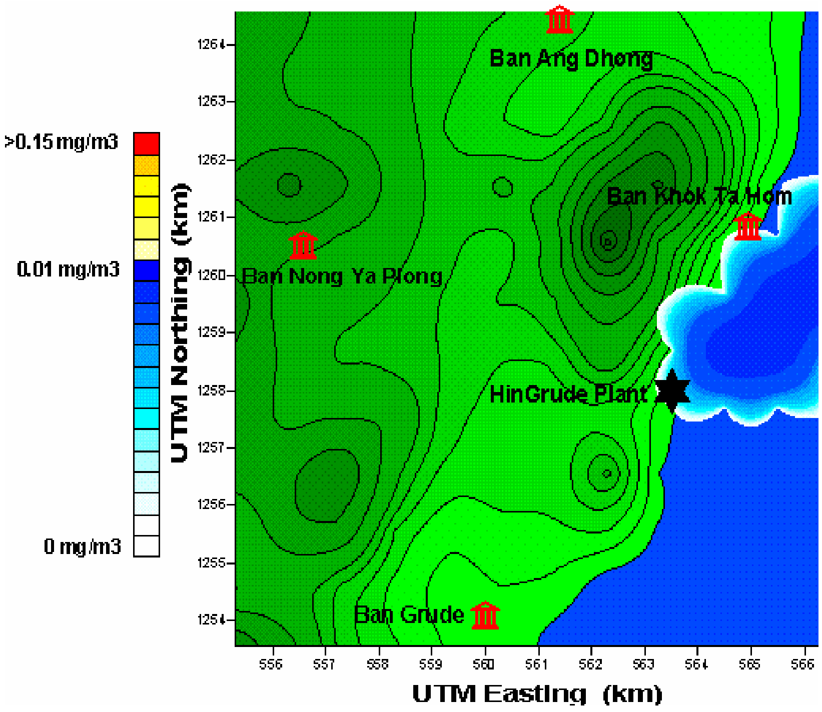
Appendix Figure J78 6th hour dispersion of PM_{10} in winter



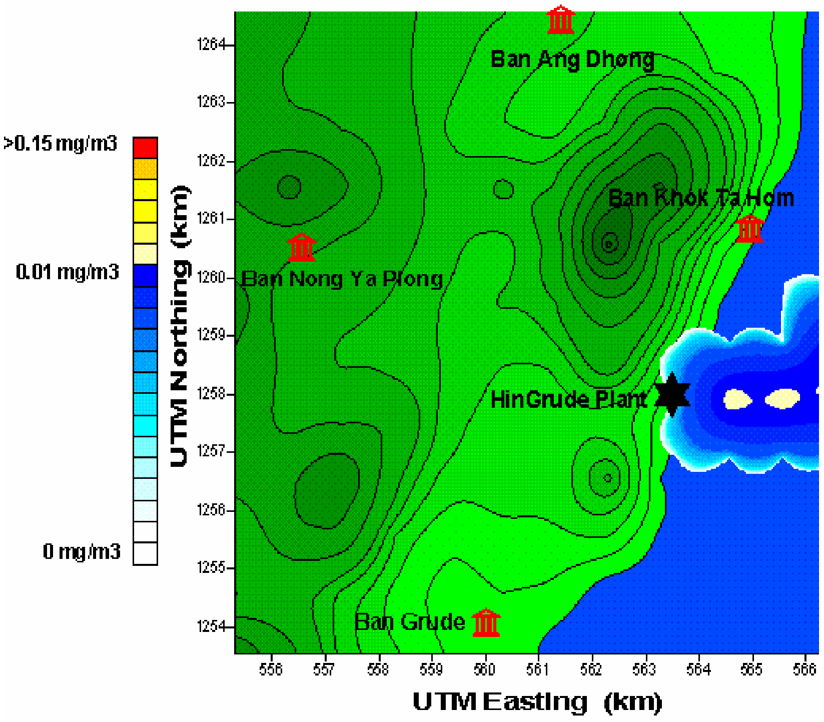
Appendix Figure J79 7th hour dispersion of PM_{10} in winter



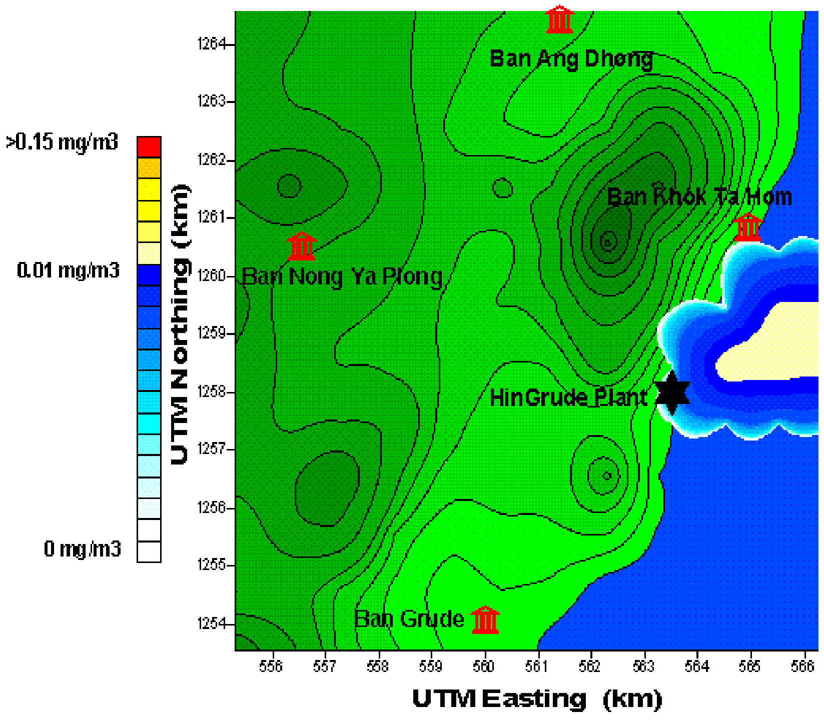
Appendix Figure J80 8th hour dispersion of PM_{10} in winter



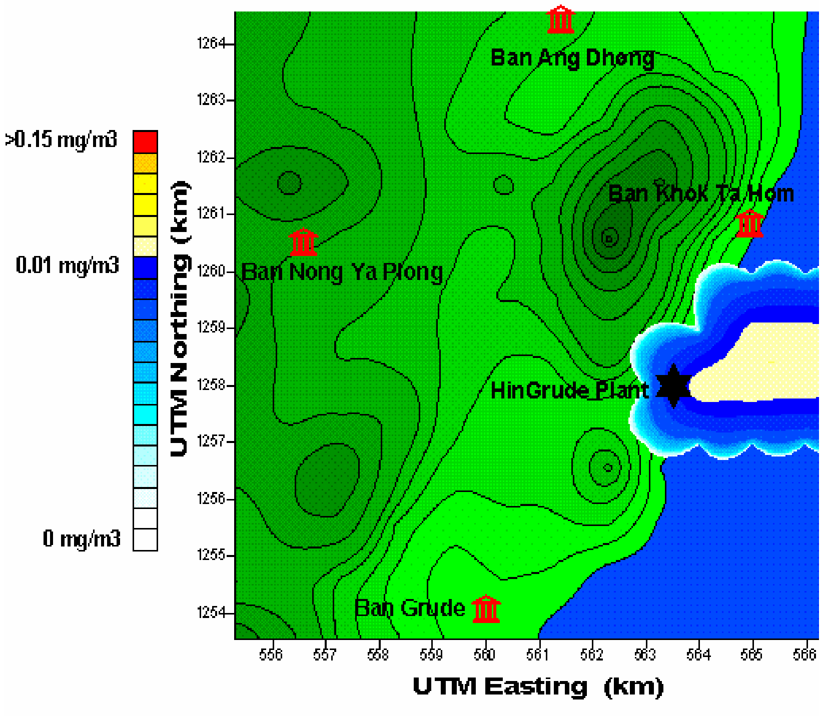
Appendix Figure J81 9th hour dispersion of PM_{10} in winter



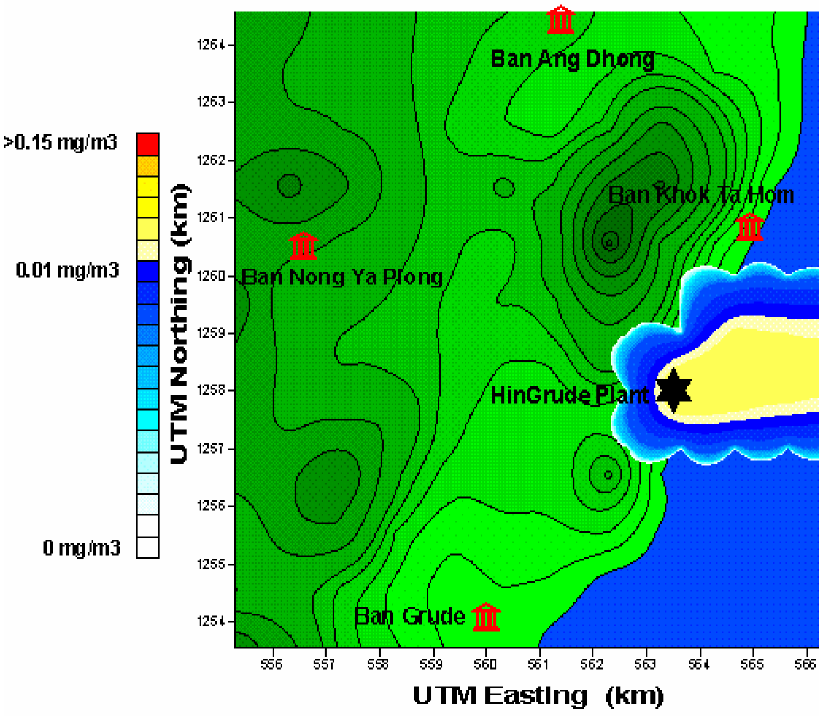
Appendix Figure J82 10th hour dispersion of PM_{10} in winter



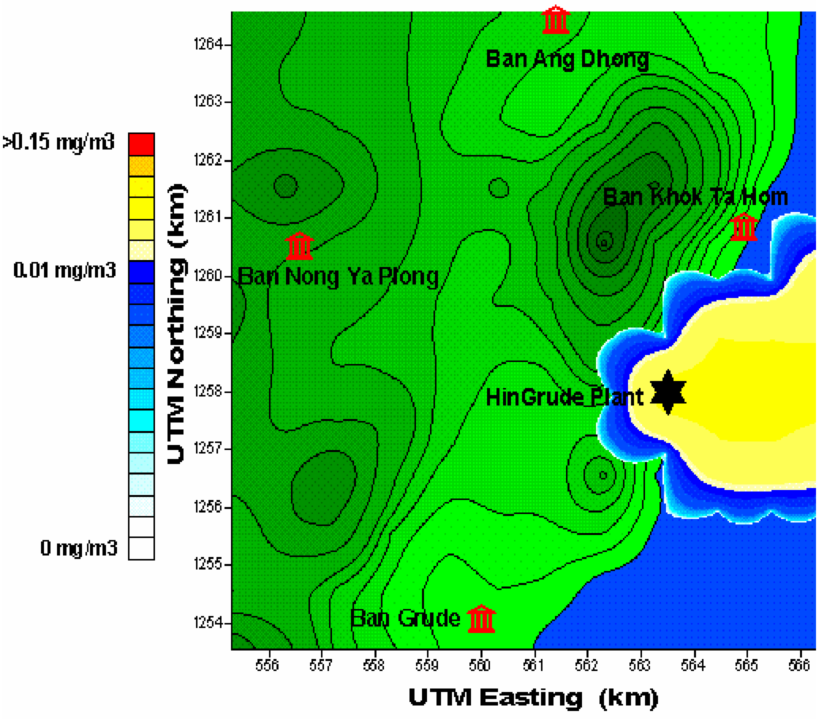
Appendix Figure J83 11th hour dispersion of PM_{10} in winter



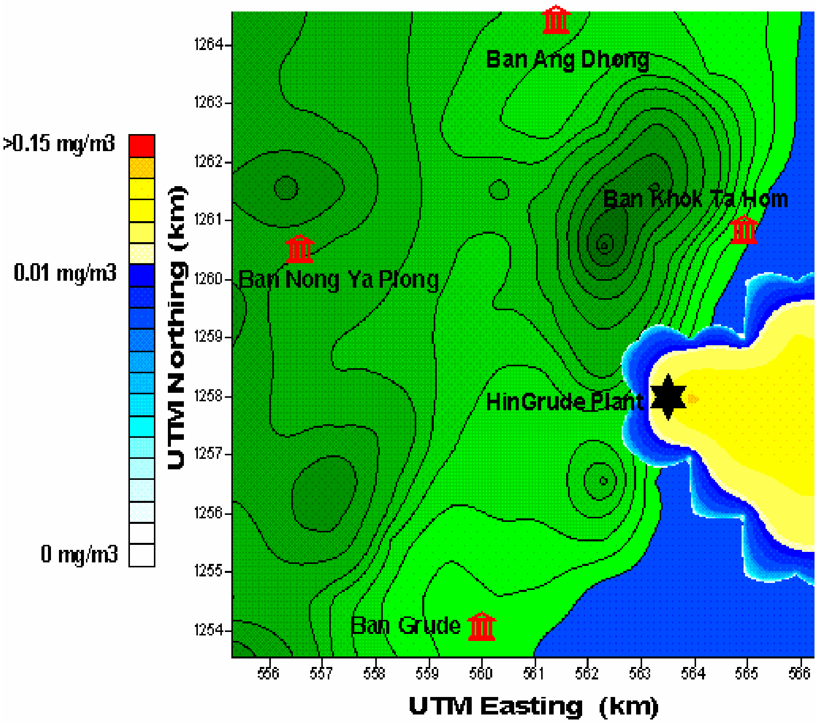
Appendix Figure J84 12th hour dispersion of PM_{10} in winter



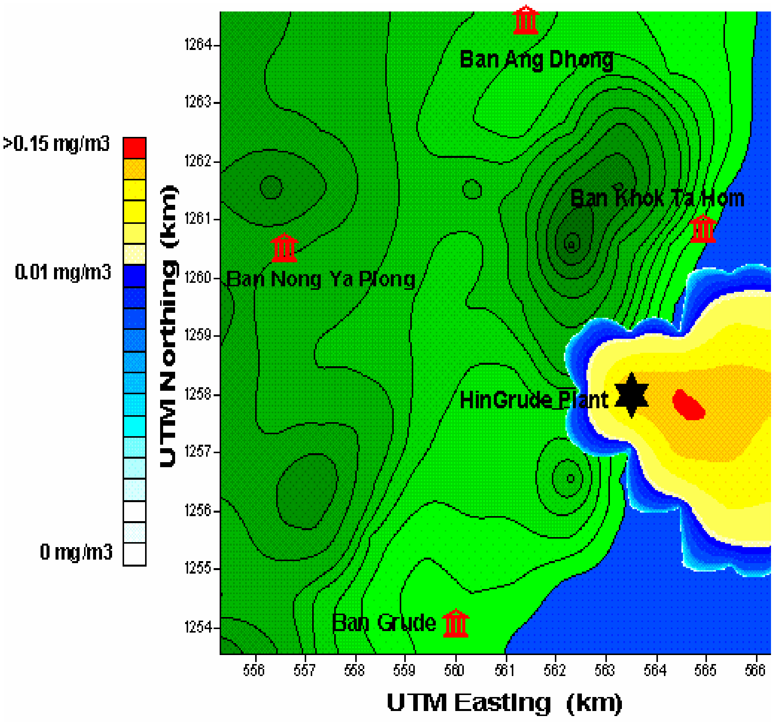
Appendix Figure J85 13th hour dispersion of PM_{10} in winter



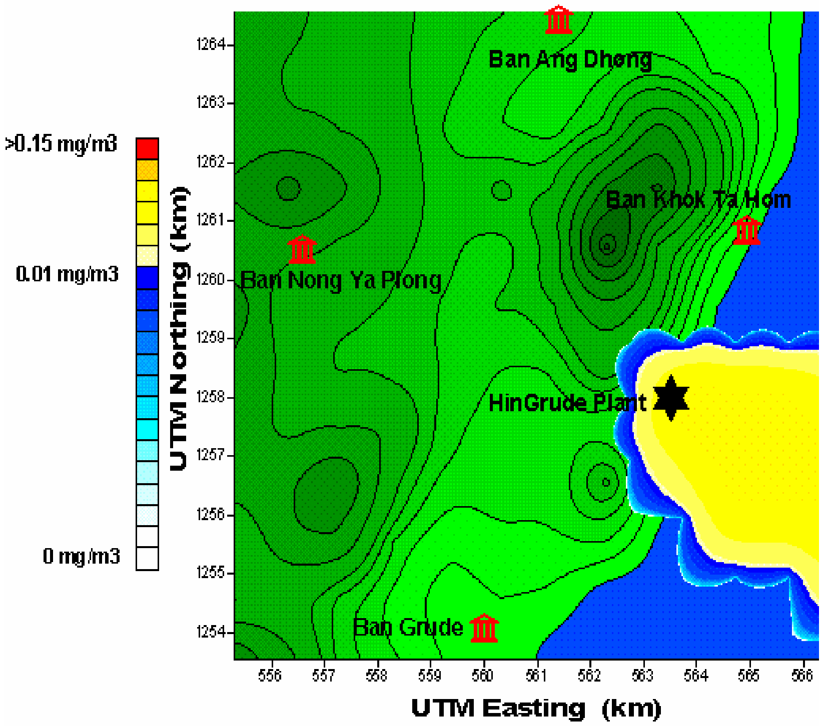
Appendix Figure J86 14th hour dispersion of PM_{10} in winter



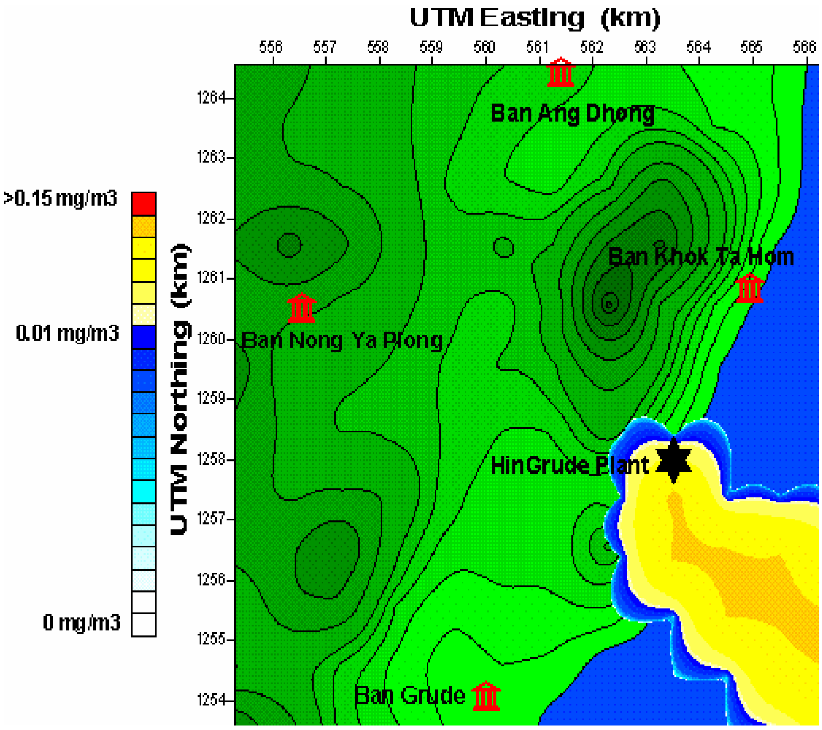
Appendix Figure J87 15th hour dispersion of PM_{10} in winter



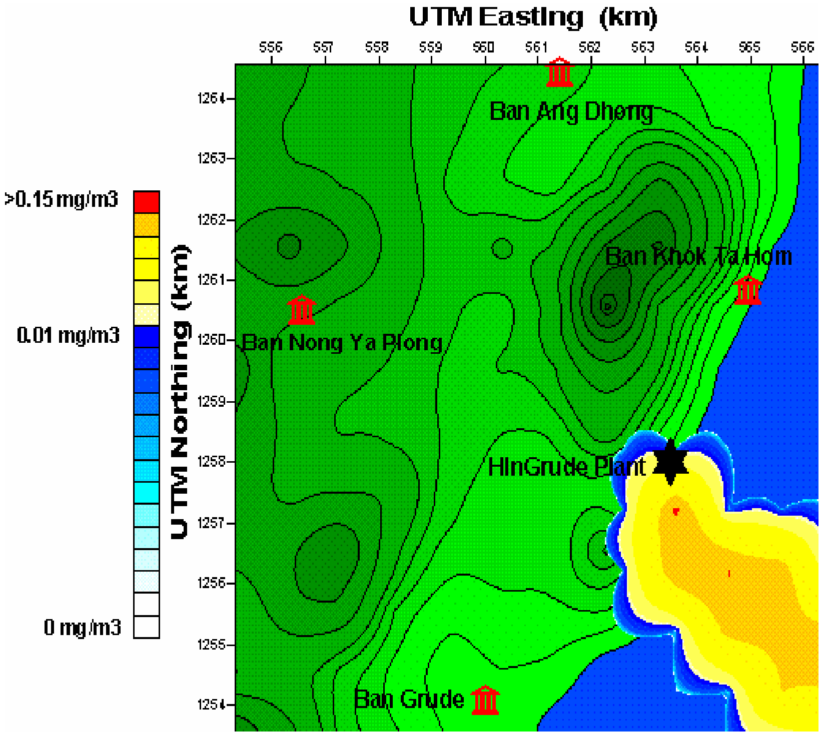
Appendix Figure J88 16th hour dispersion of PM_{10} in winter



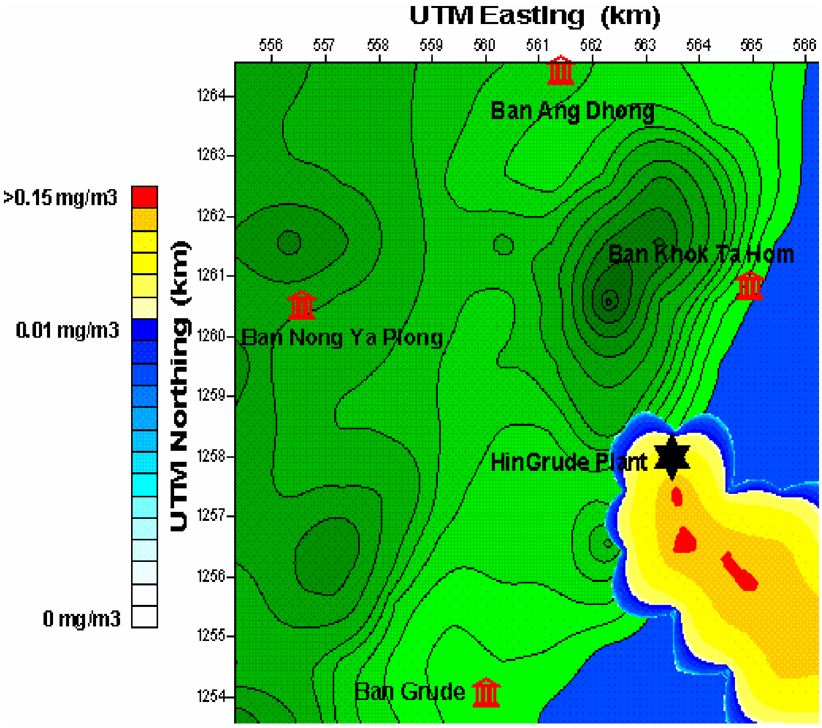
Appendix Figure J89 17th hour dispersion of PM_{10} in winter



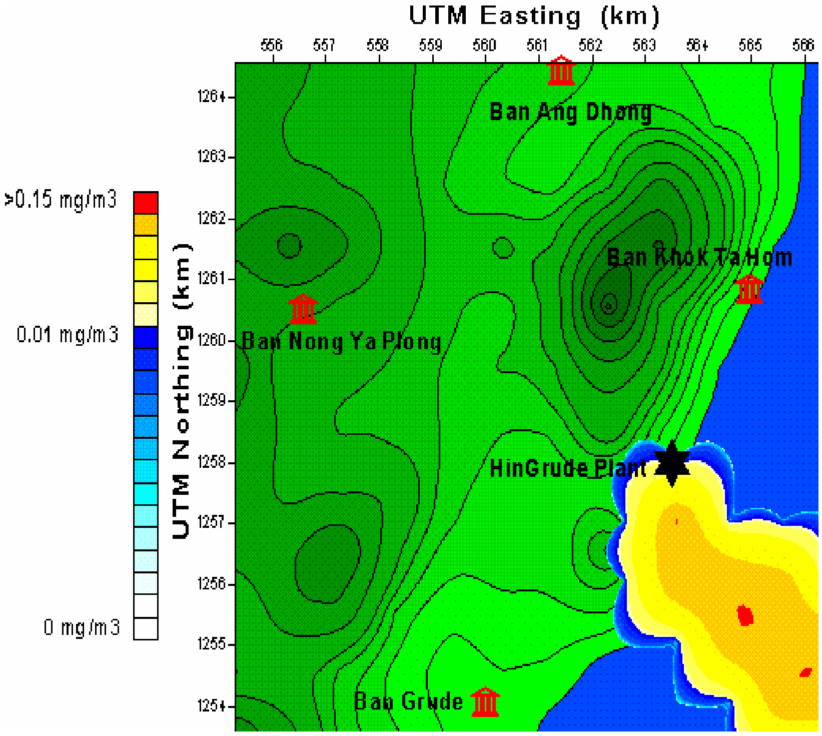
Appendix Figure J90 18th hour dispersion of PM_{10} in winter



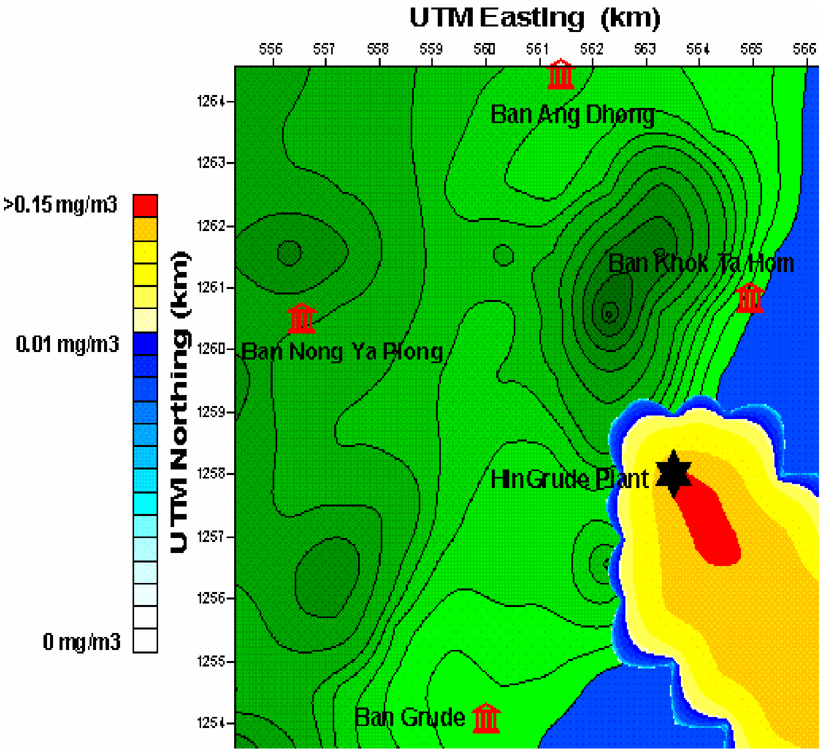
Appendix Figure J91 19th hour dispersion of PM_{10} in winter



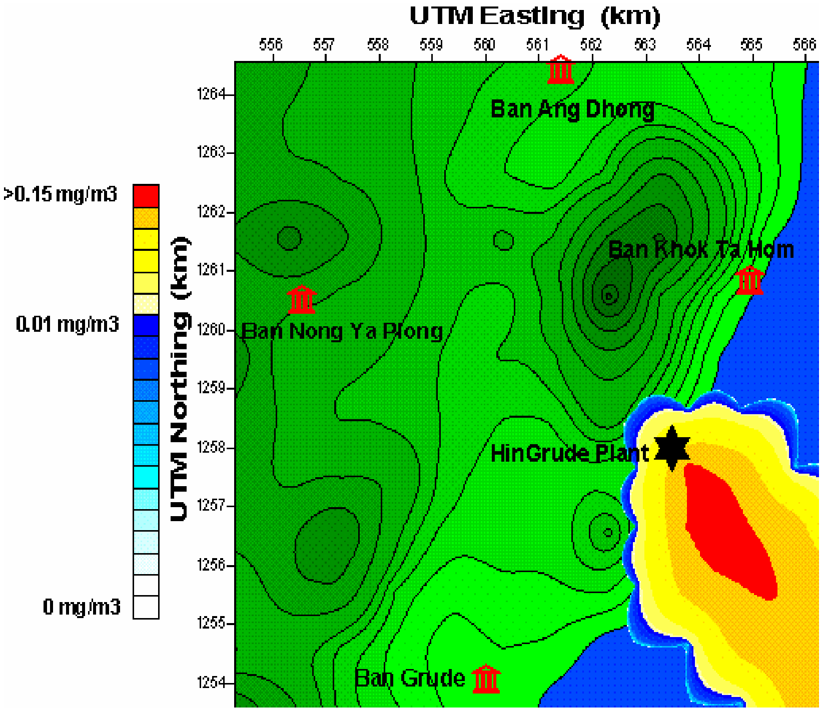
Appendix Figure J92 20th hour dispersion of PM_{10} in winter



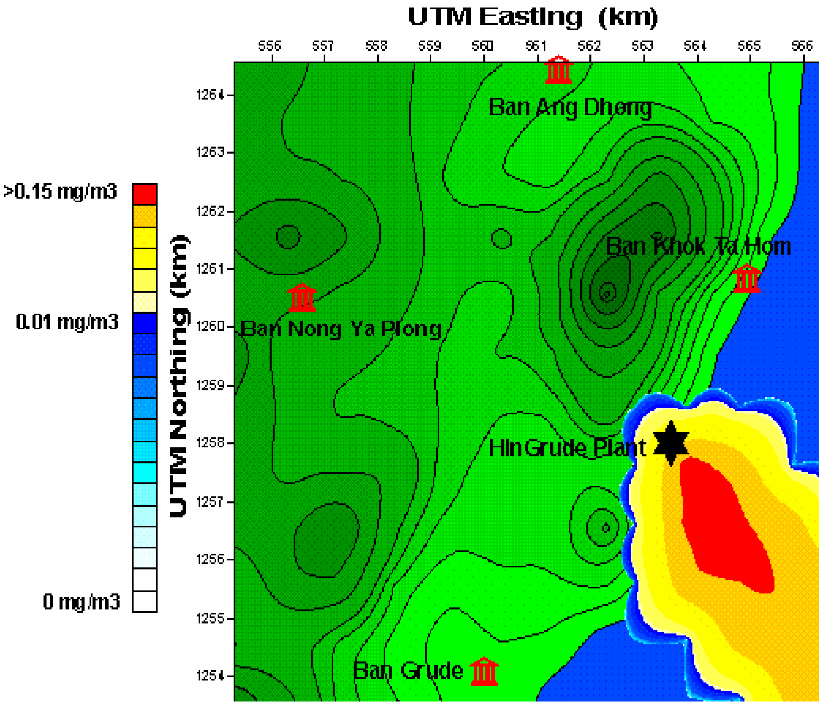
Appendix Figure J93 21st hour dispersion of PM_{10} in winter



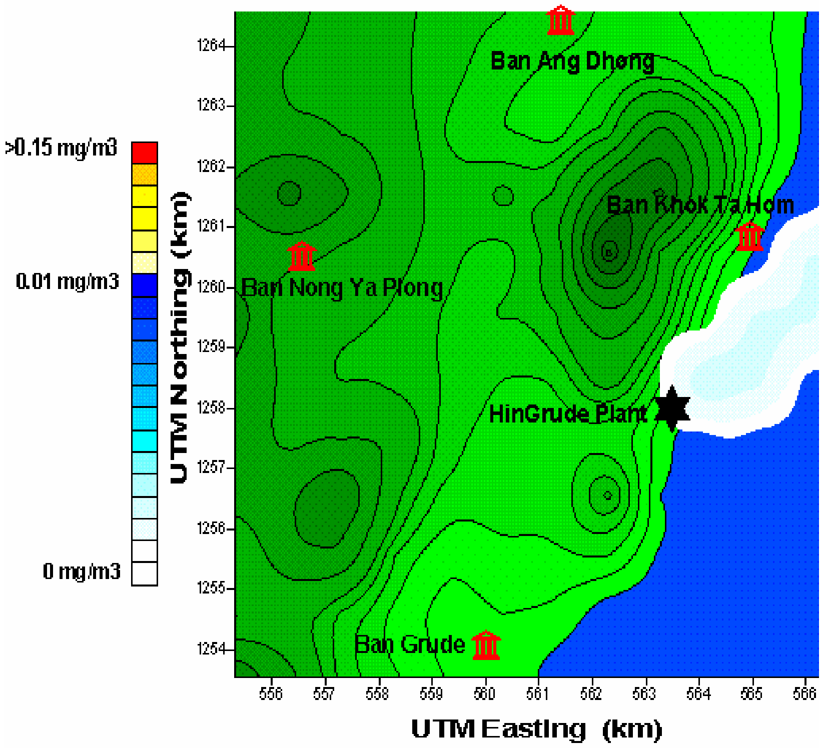
Appendix Figure J94 22nd hour dispersion of PM_{10} in winter



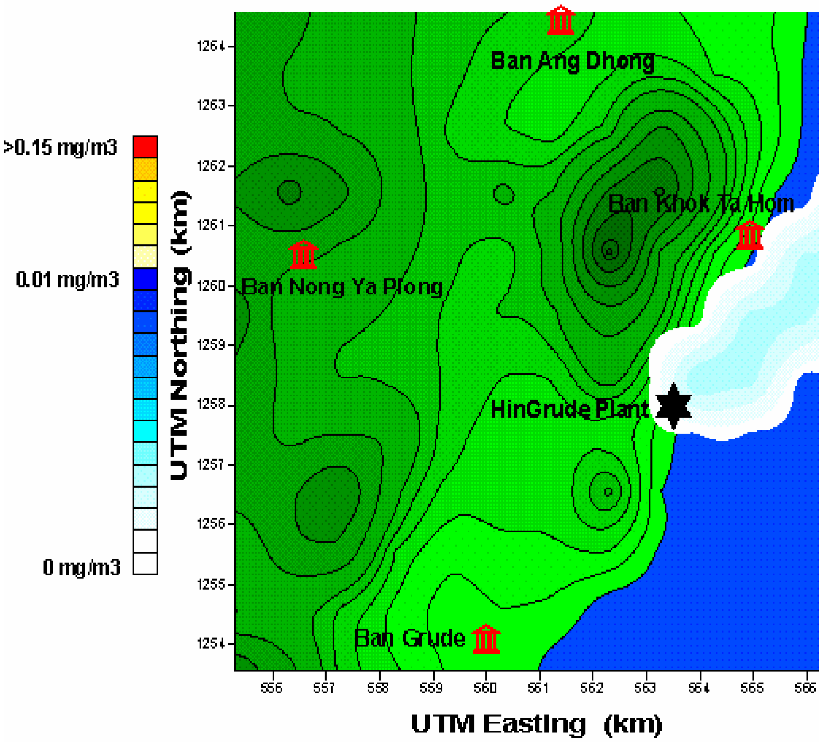
Appendix Figure J95 23rd hour dispersion of PM_{10} in winter



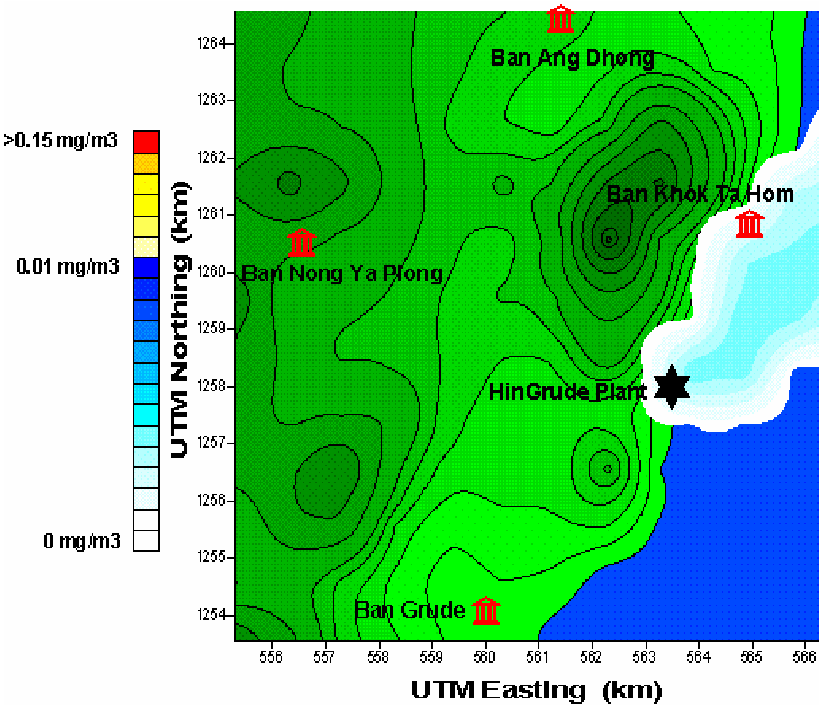
Appendix Figure J96 24th hour dispersion of PM_{10} in winter



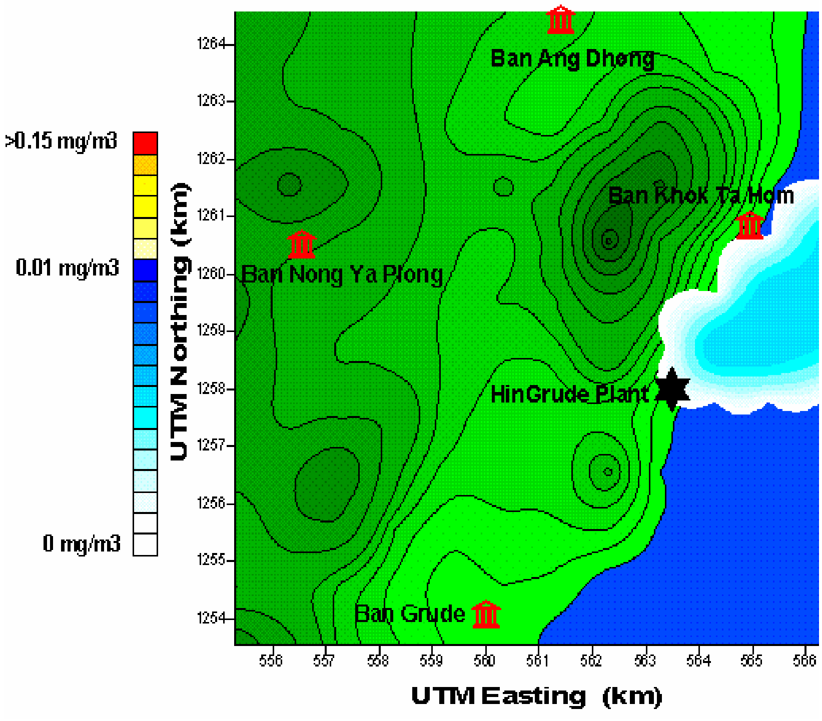
Appendix Figure J97 1st hour dispersion of PM_{10} in summer



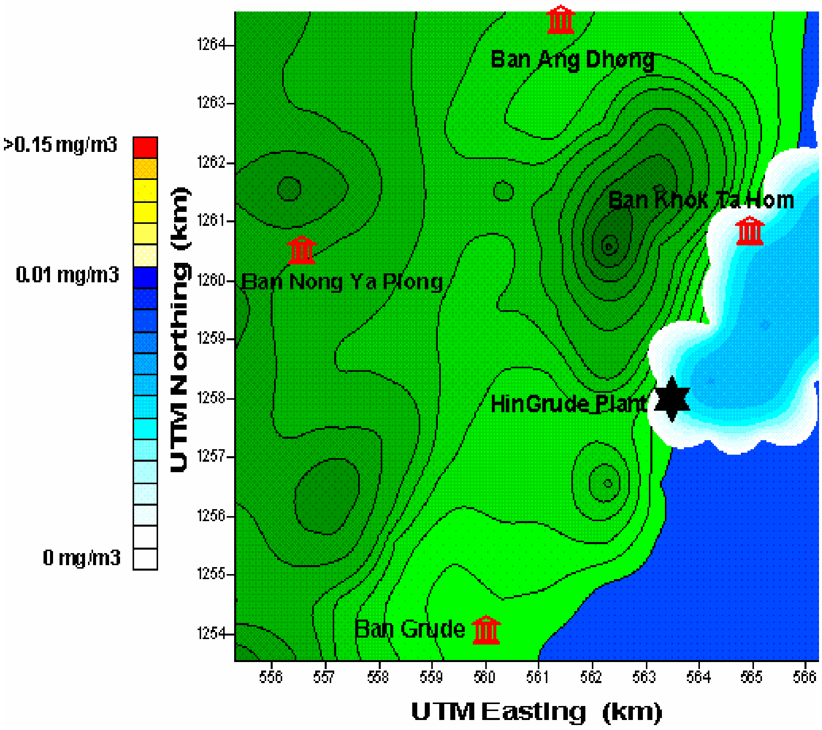
Appendix Figure J98 2nd hour dispersion of PM_{10} in summer



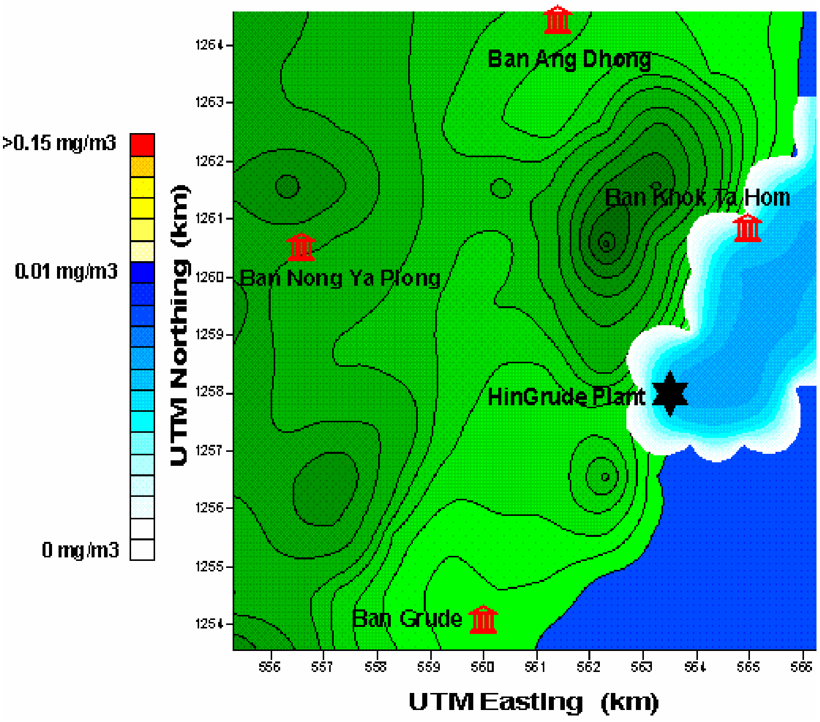
Appendix Figure J99 3rd hour dispersion of PM_{10} in summer



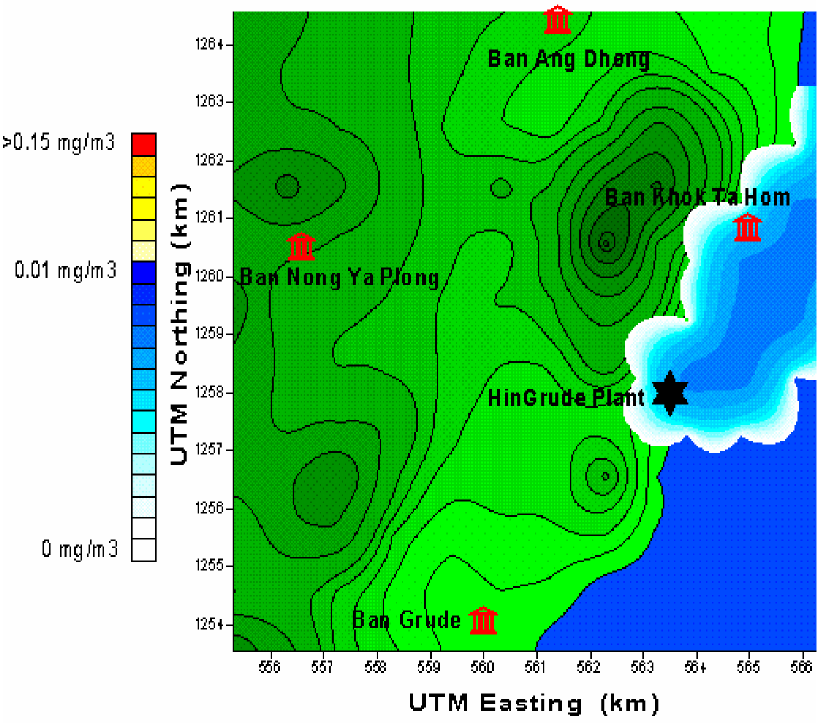
Appendix Figure J100 4th hour dispersion of PM_{10} in summer



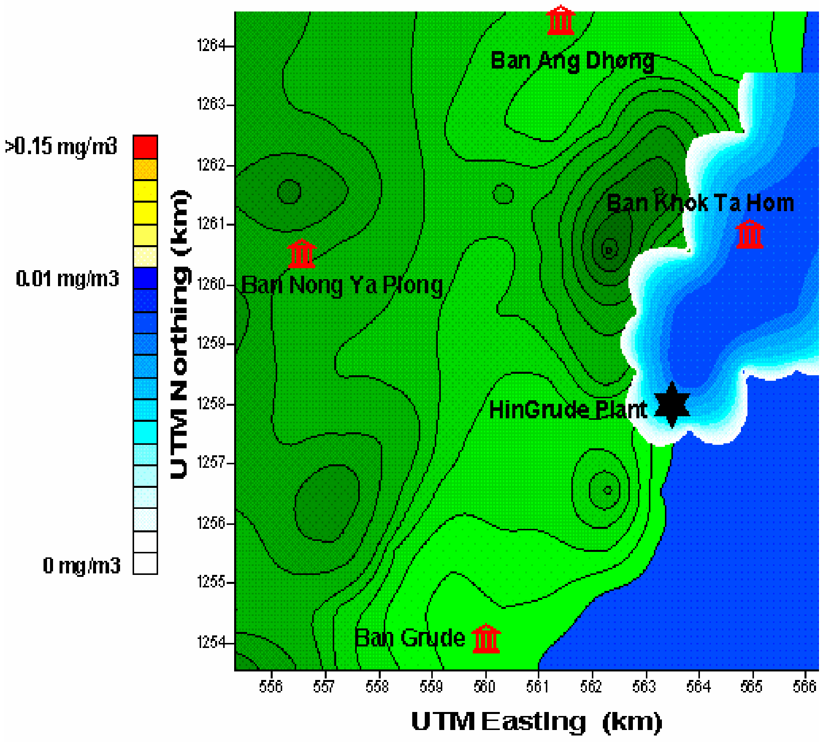
Appendix Figure J101 5th hour dispersion of PM_{10} in summer



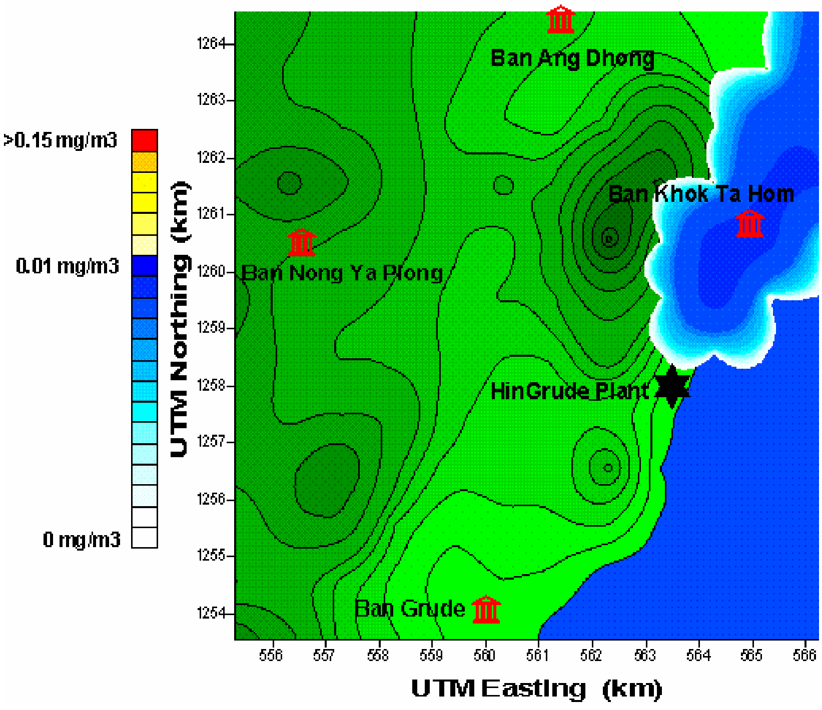
Appendix Figure J102 6th hour dispersion of PM_{10} in summer



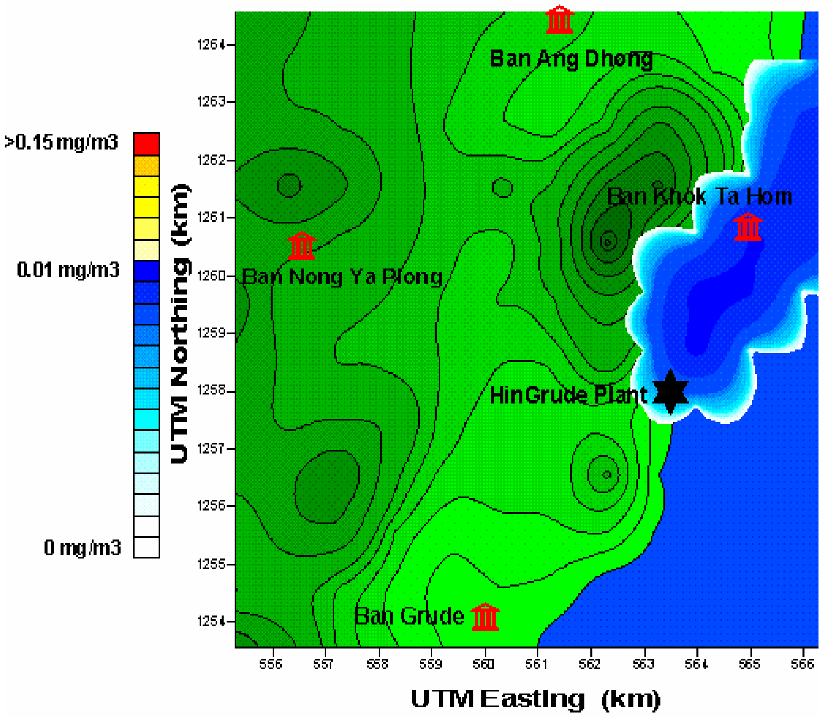
Appendix Figure J103 7th hour dispersion of PM_{10} in summer



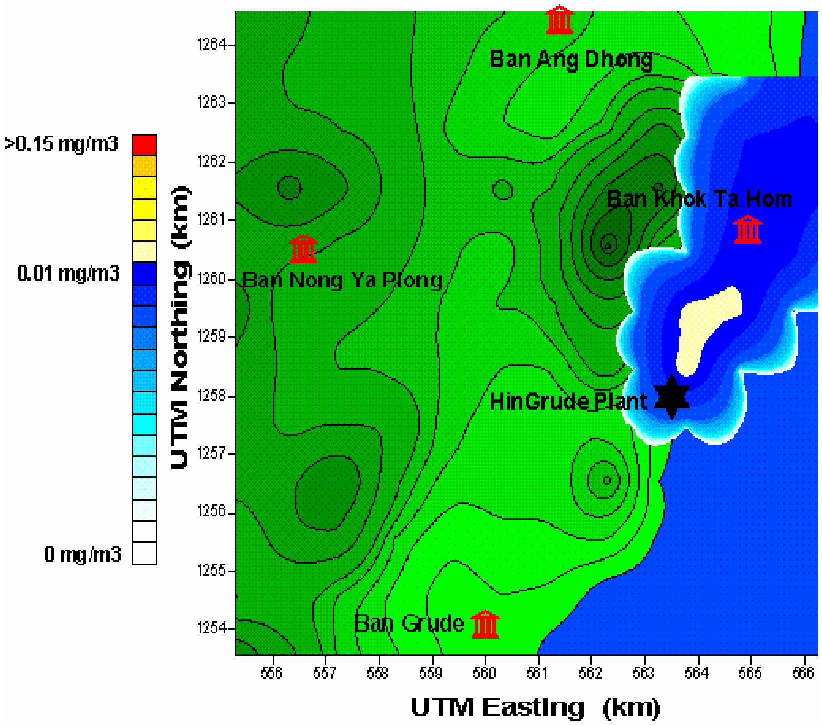
Appendix Figure J104 8th hour dispersion of PM_{10} in summer



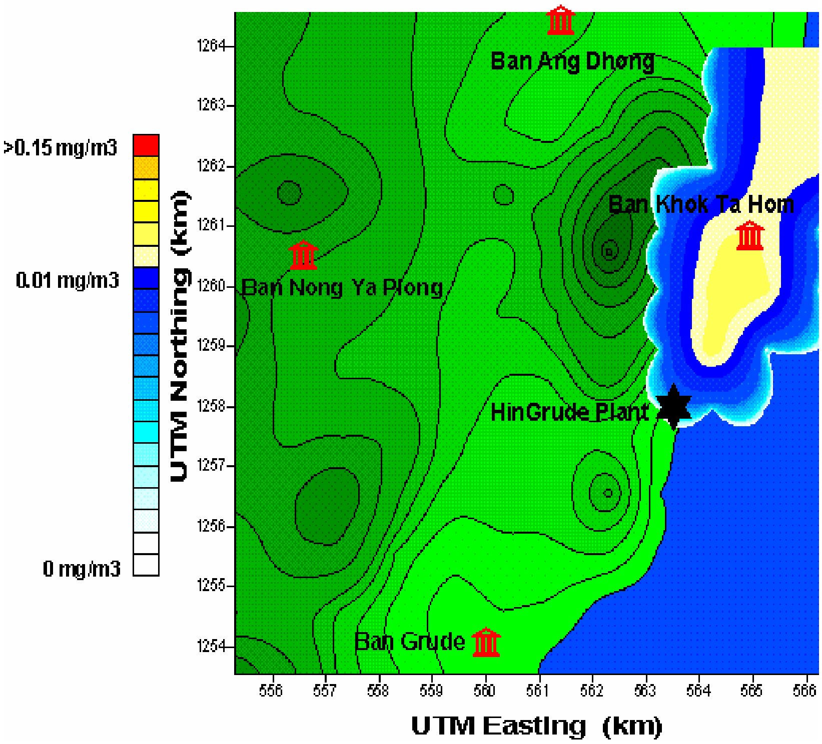
Appendix Figure J105 9th hour dispersion of PM_{10} in summer



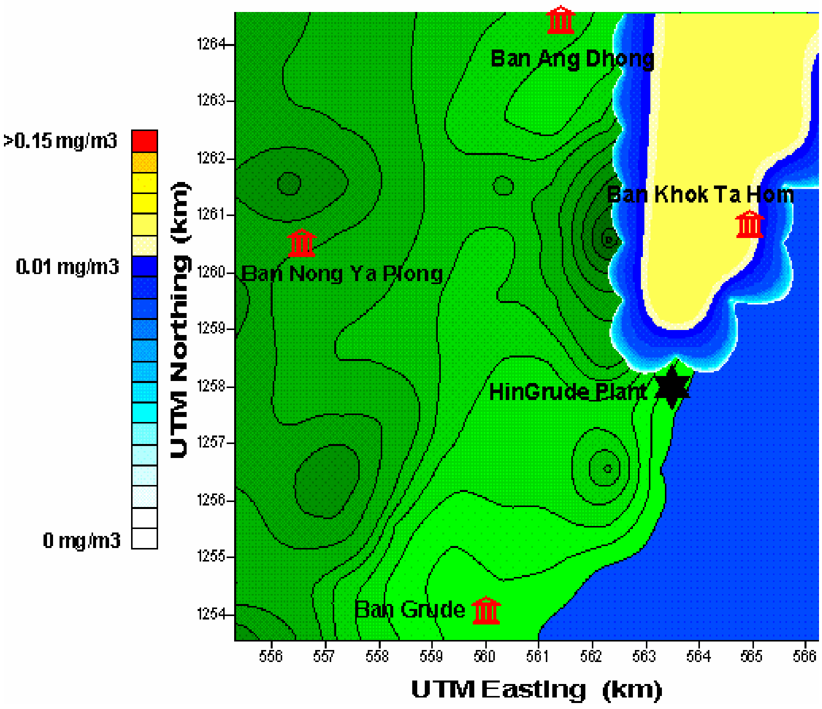
Appendix Figure J106 10th hour dispersion of PM_{10} in summer



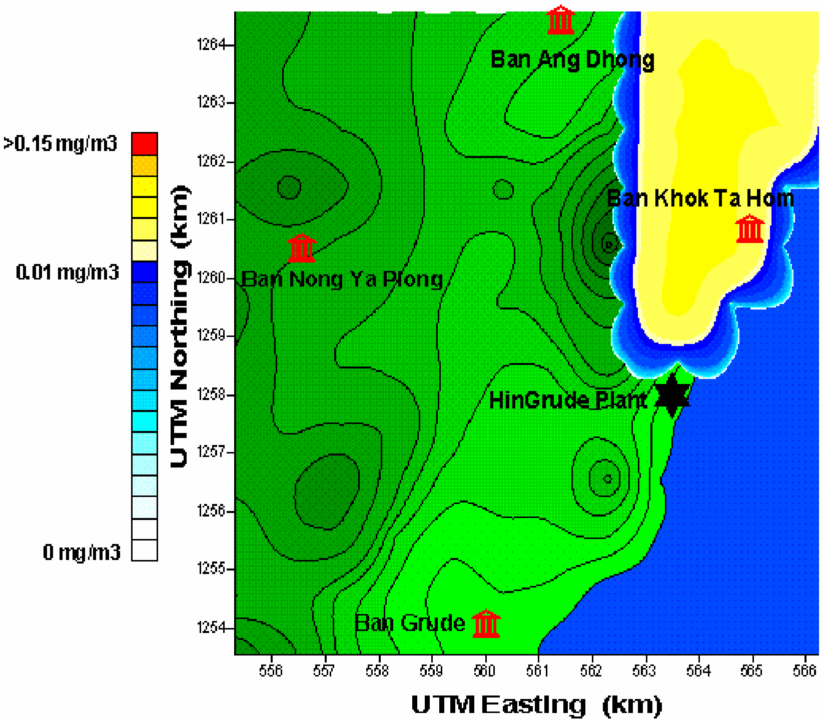
Appendix Figure J107 11th hour dispersion of PM_{10} in summer



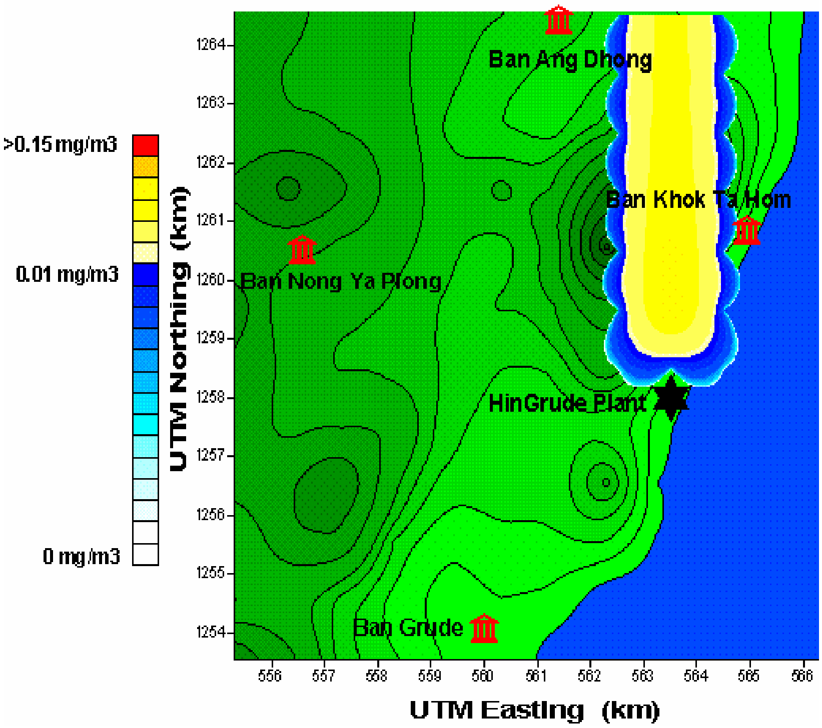
Appendix Figure J108 12th hour dispersion of PM_{10} in summer



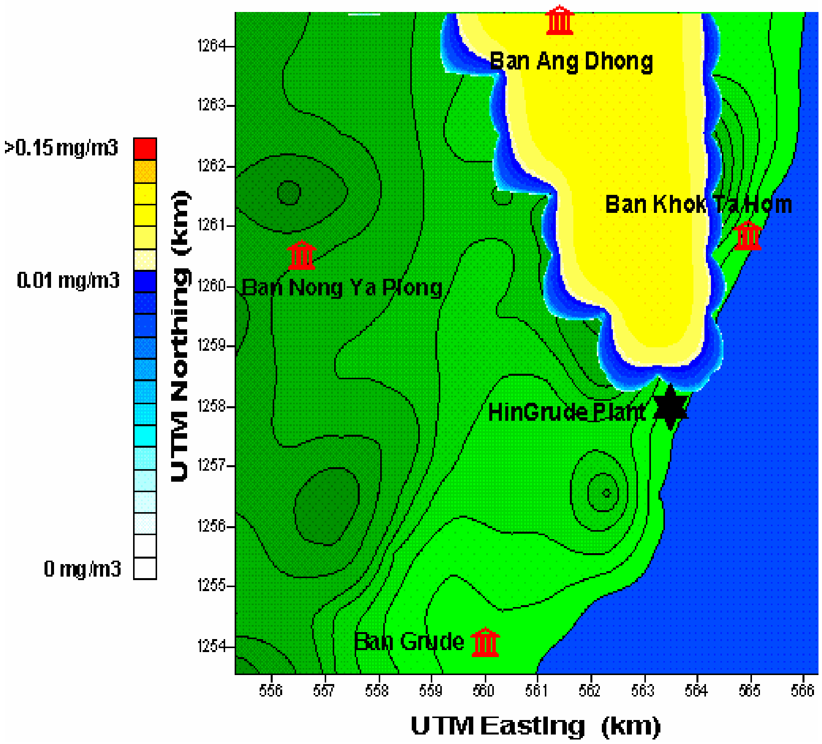
Appendix Figure J109 13th hour dispersion of PM_{10} in summer



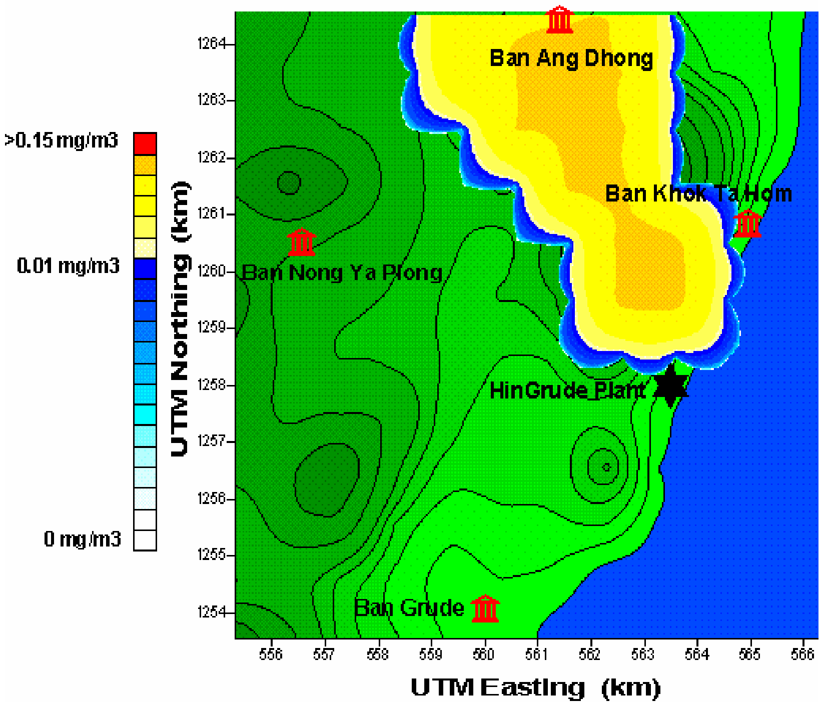
Appendix Figure J110 14th hour dispersion of PM_{10} in summer



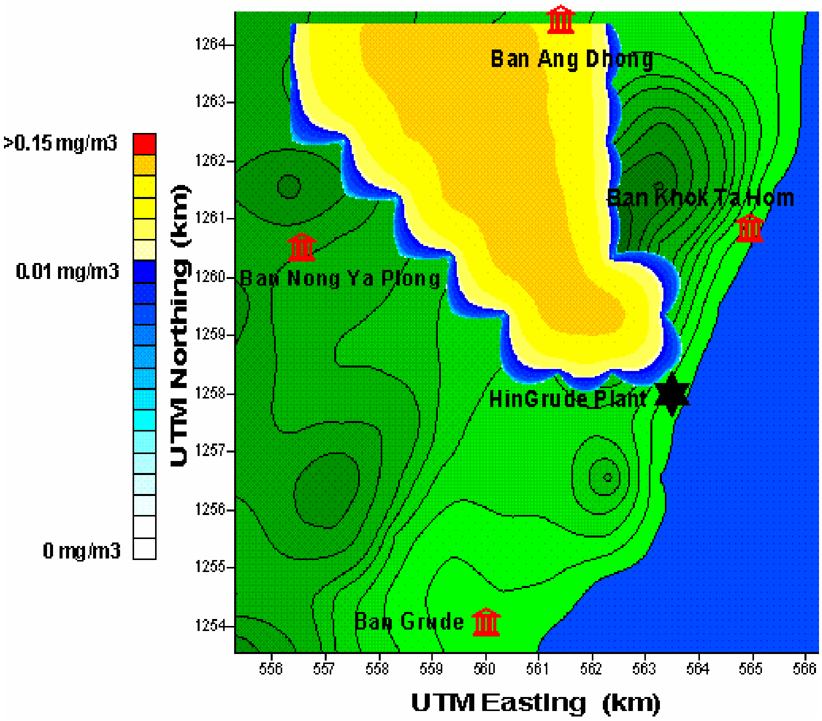
Appendix Figure J111 15th hour dispersion of PM_{10} in summer



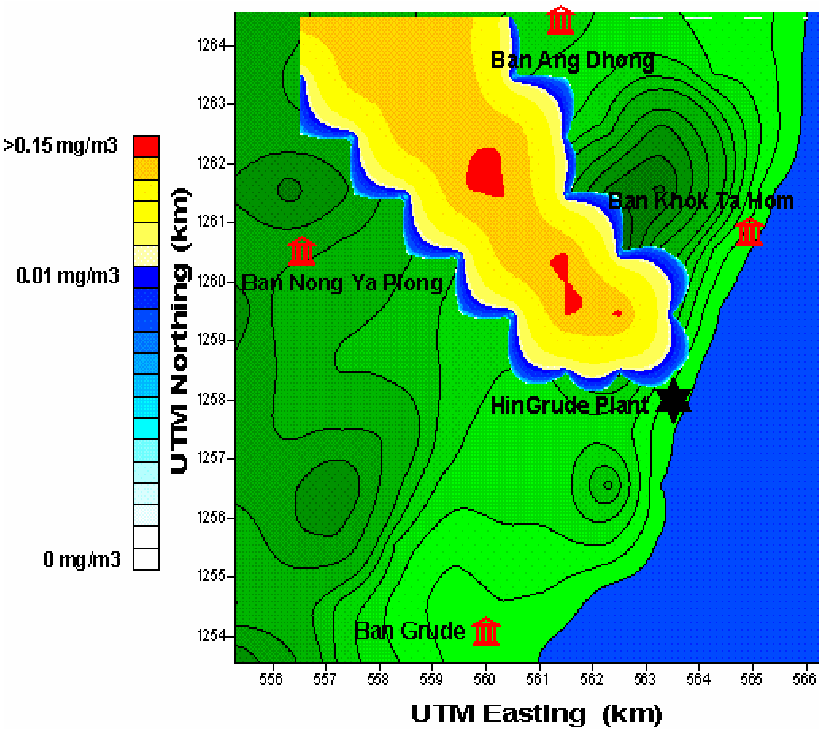
Appendix Figure J112 16th hour dispersion of PM_{10} in summer



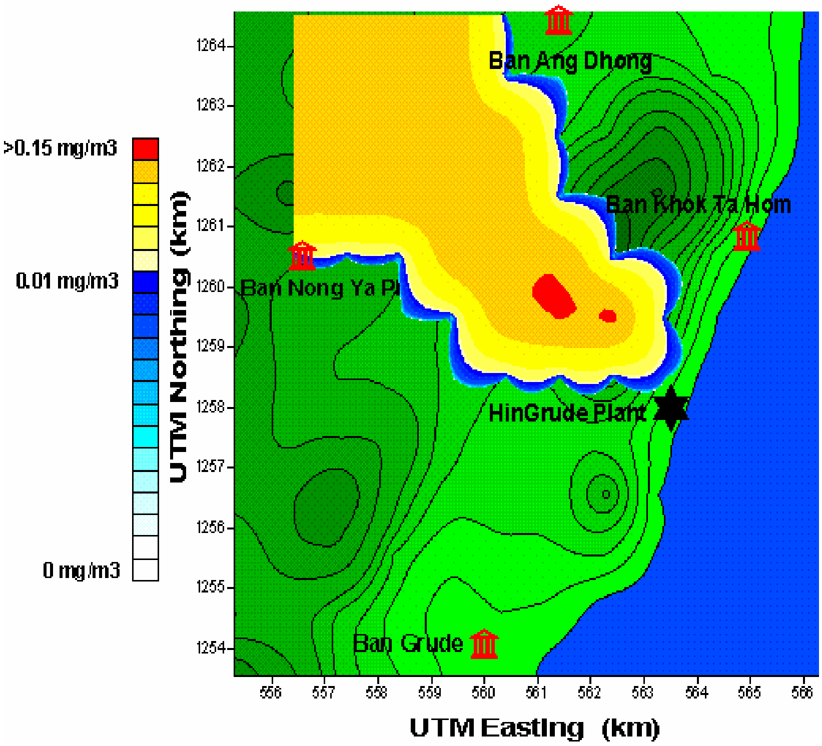
Appendix Figure J113 17th hour dispersion of PM_{10} in summer



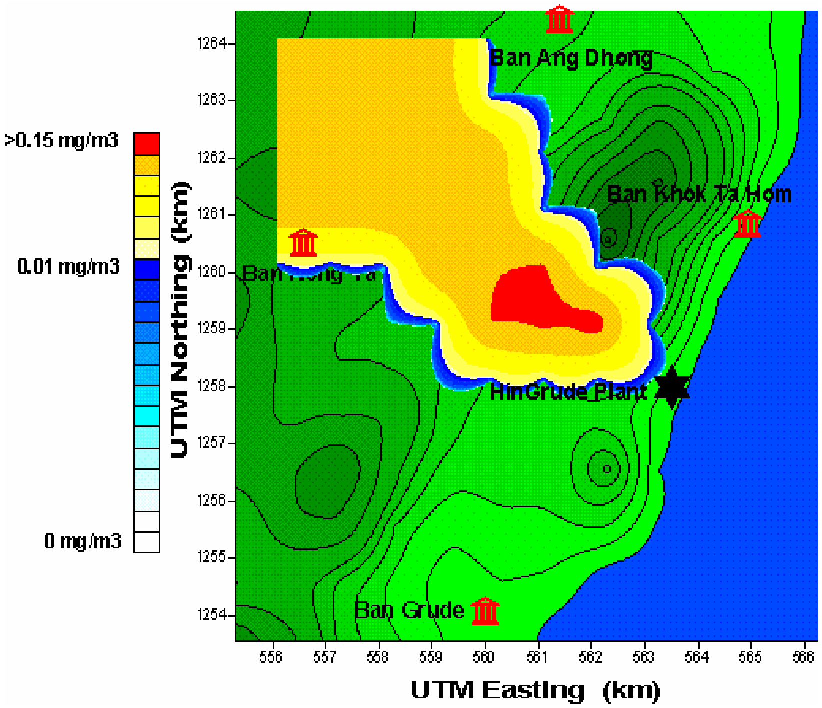
Appendix Figure J114 18th hour dispersion of PM_{10} in summer



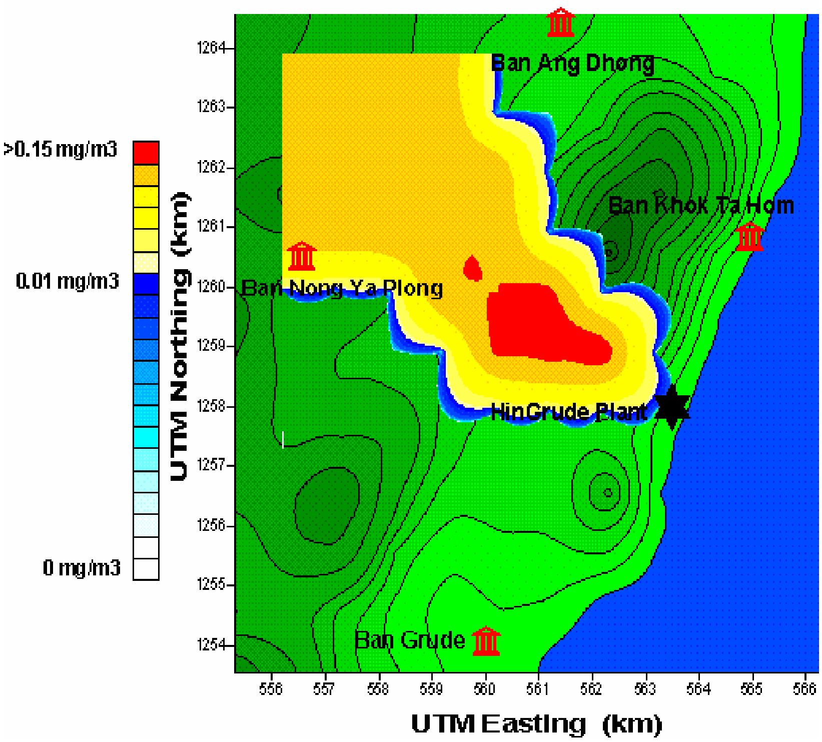
Appendix Figure J115 19th hour dispersion of PM_{10} in summer



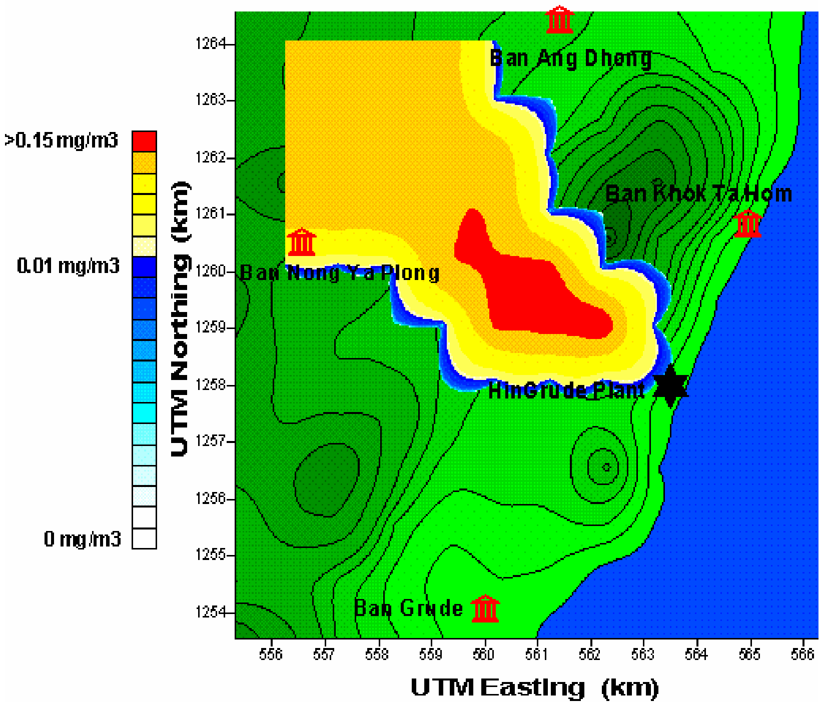
Appendix Figure J116 20th hour dispersion of PM_{10} in summer



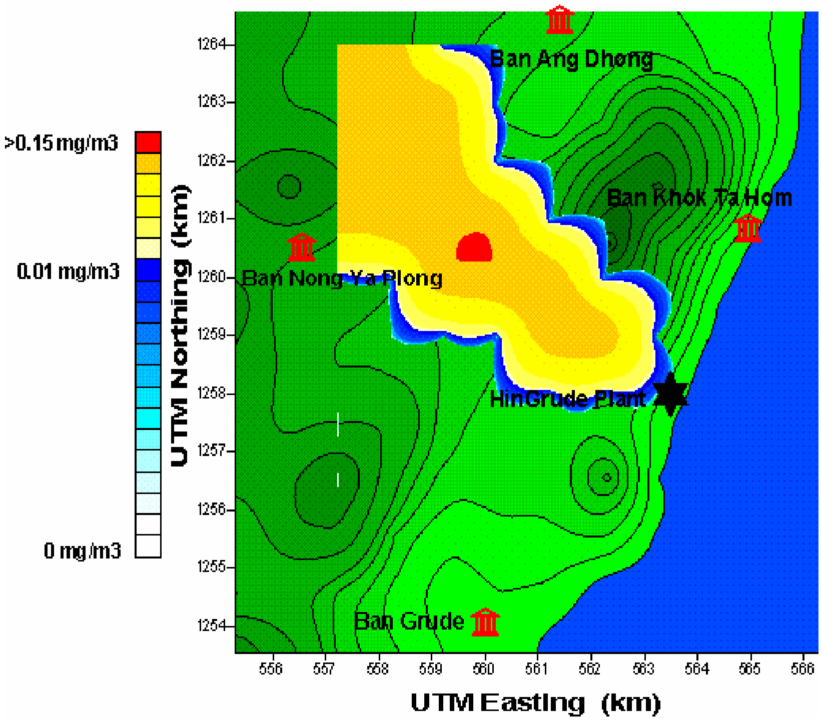
Appendix Figure J117 21st hour dispersion of PM_{10} in summer



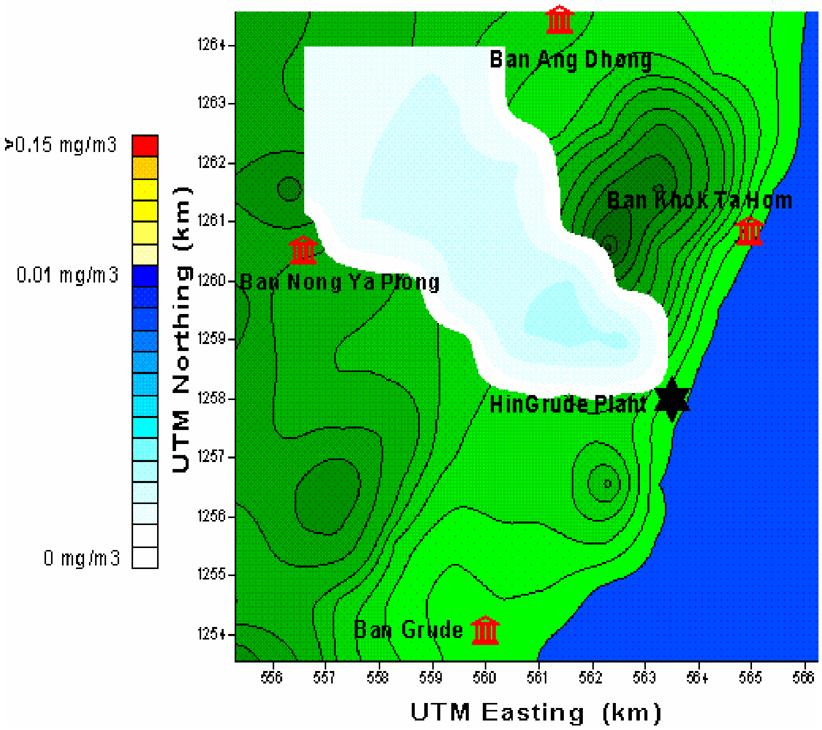
Appendix Figure J118 22nd hour dispersion of PM_{10} in summer



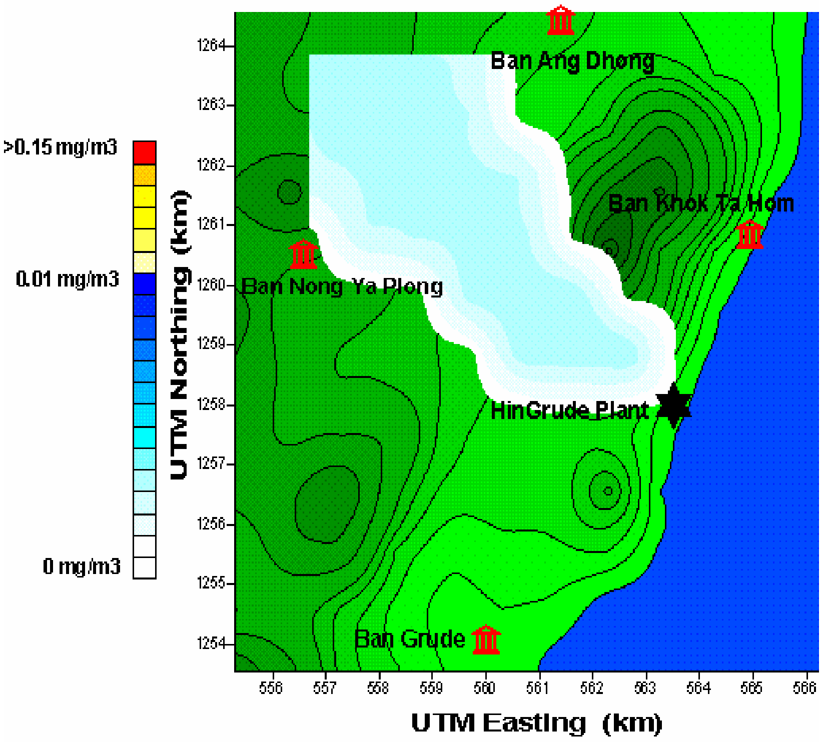
Appendix Figure J119 23rd hour dispersion of PM_{10} in summer



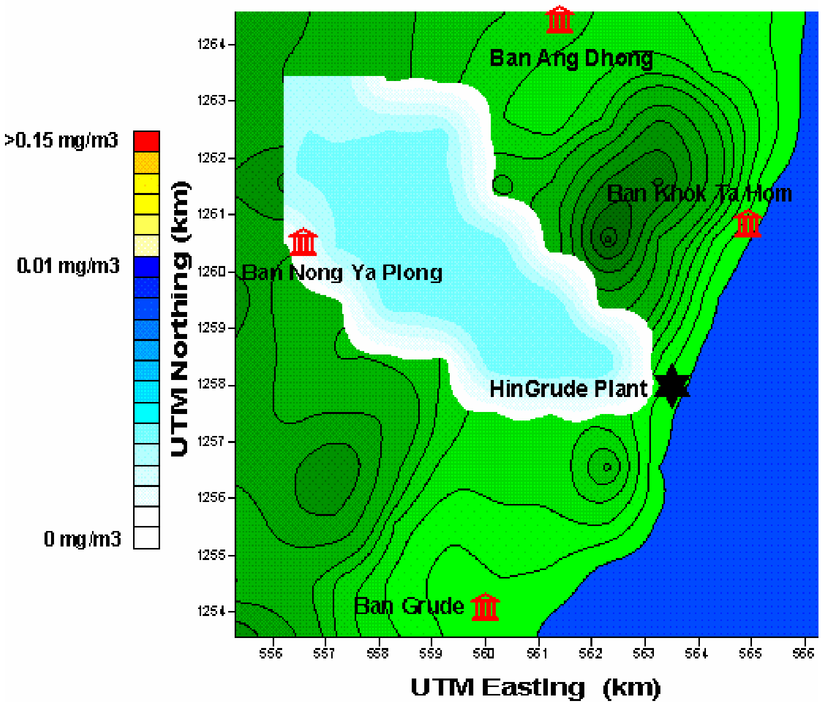
Appendix Figure J120 24th hour dispersion of PM_{10} in summer



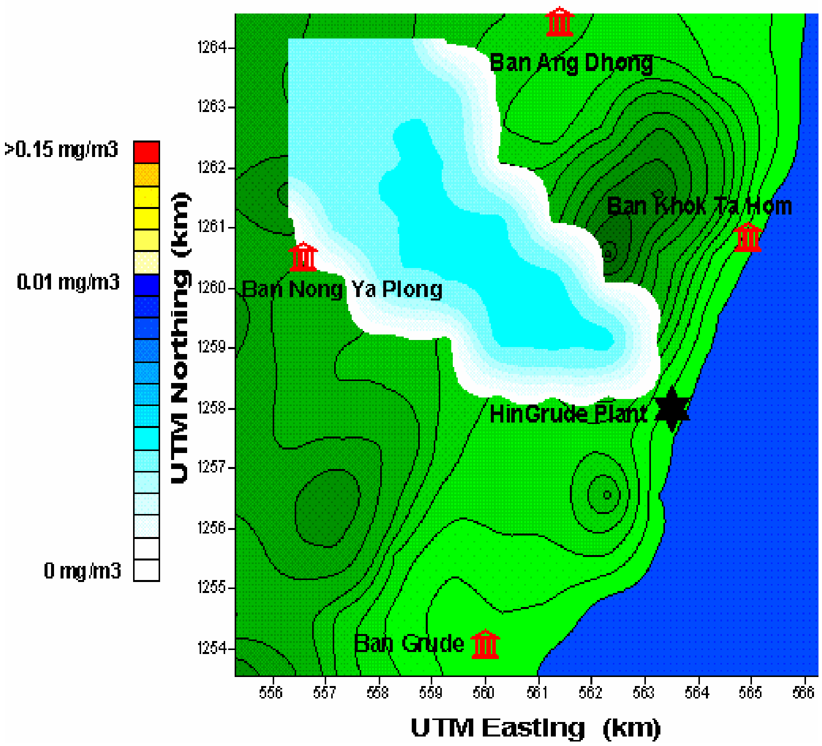
Appendix Figure J121 1st hour dispersion of PM_{10} in rainy season



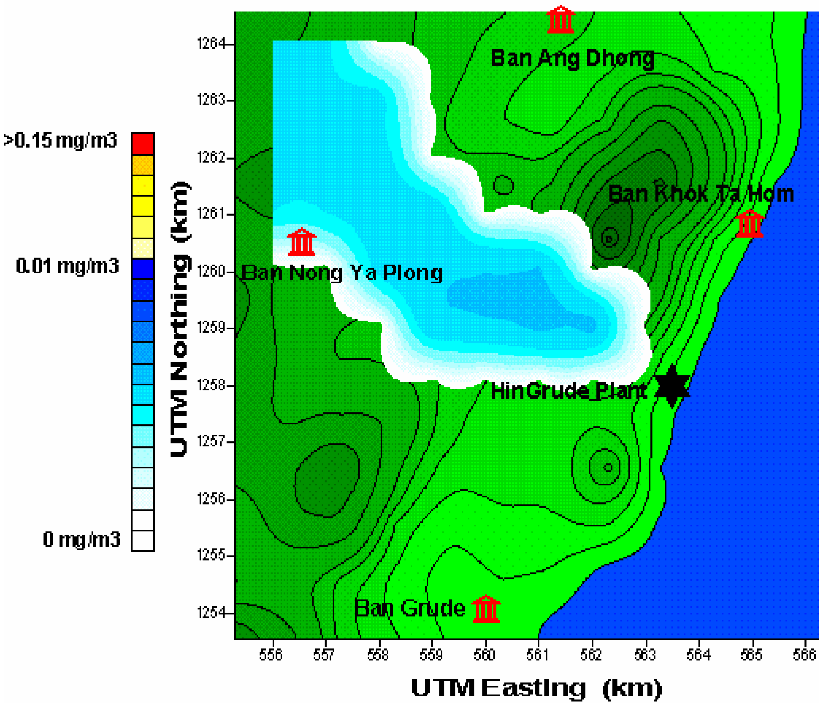
Appendix Figure J122 2nd hour dispersion of PM_{10} in rainy season



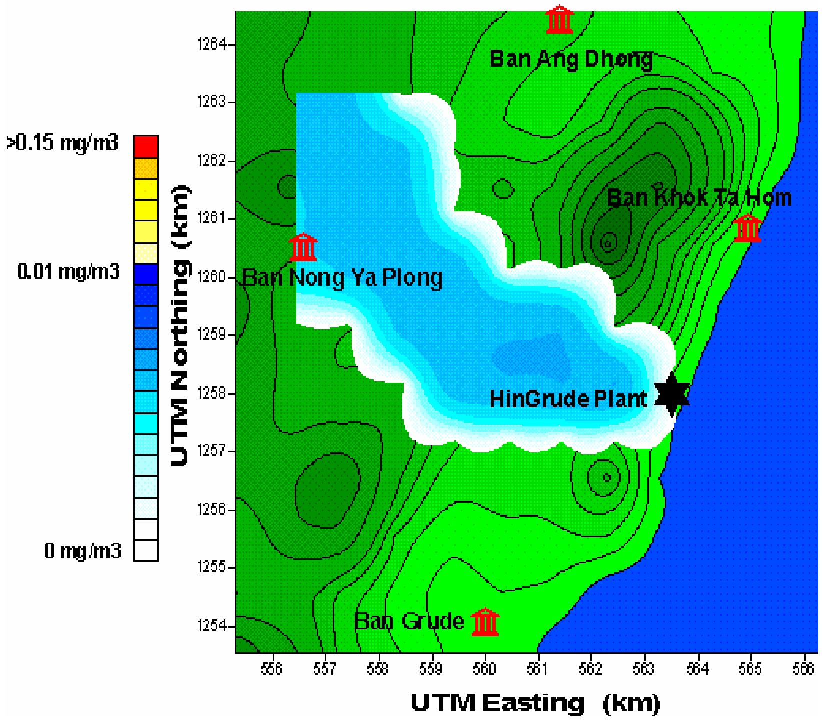
Appendix Figure J123 3rd hour dispersion of PM_{10} in rainy season



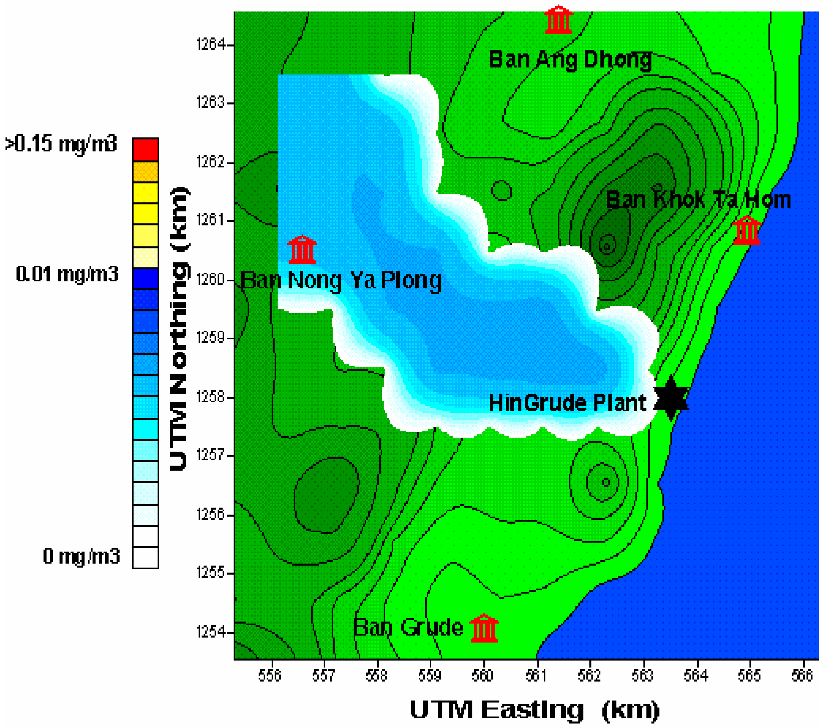
Appendix Figure J124 4th hour dispersion of PM_{10} in rainy season



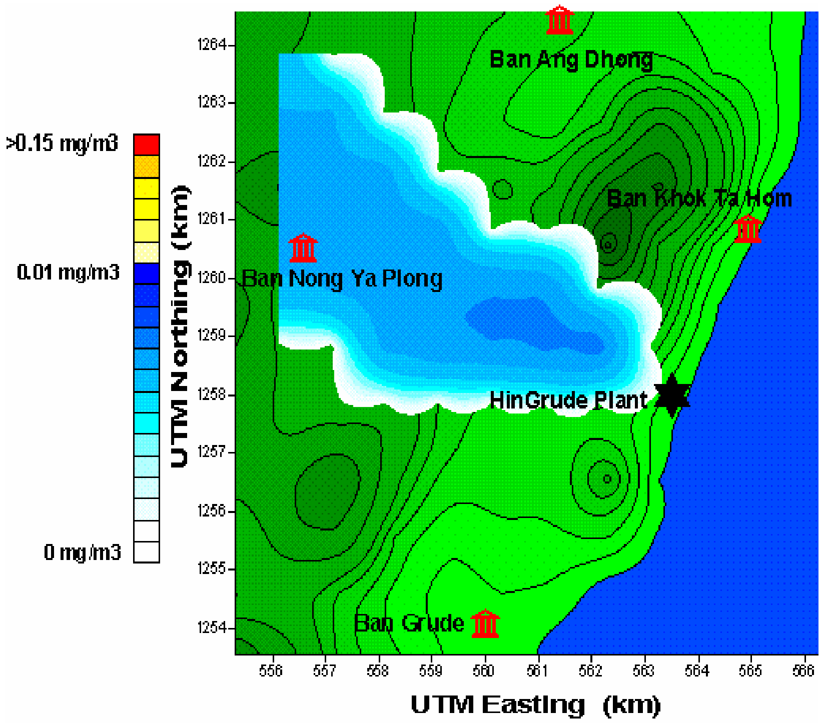
Appendix Figure J125 5th hour dispersion of PM_{10} in rainy season



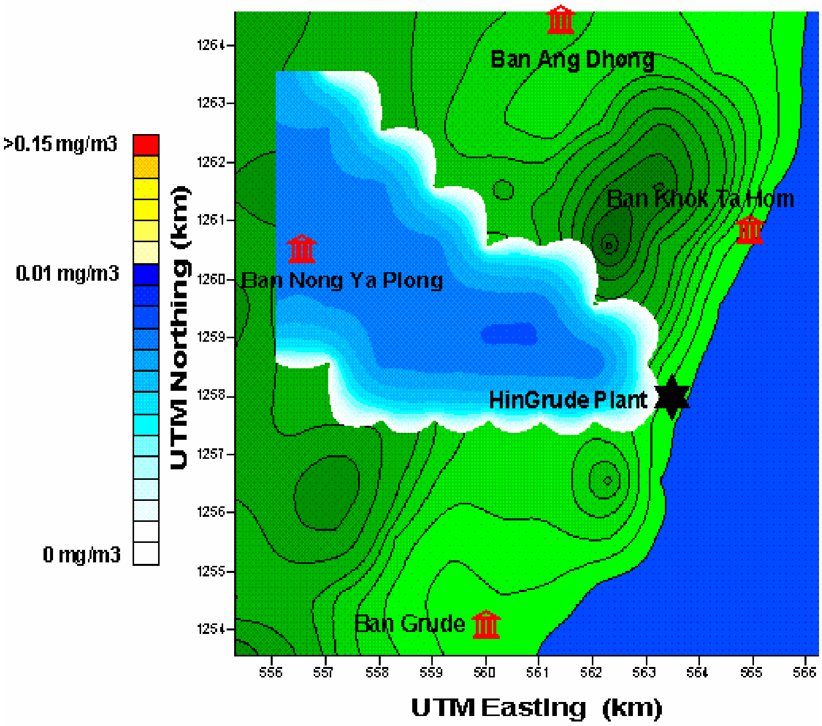
Appendix Figure J126 6th hour dispersion of PM_{10} in rainy season



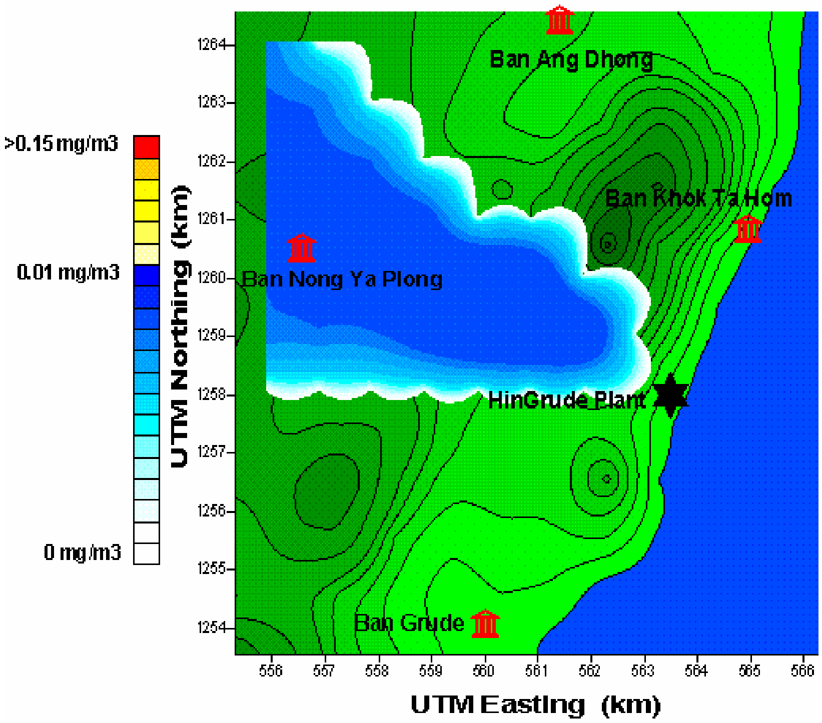
Appendix Figure J127 7th hour dispersion of PM_{10} in rainy season



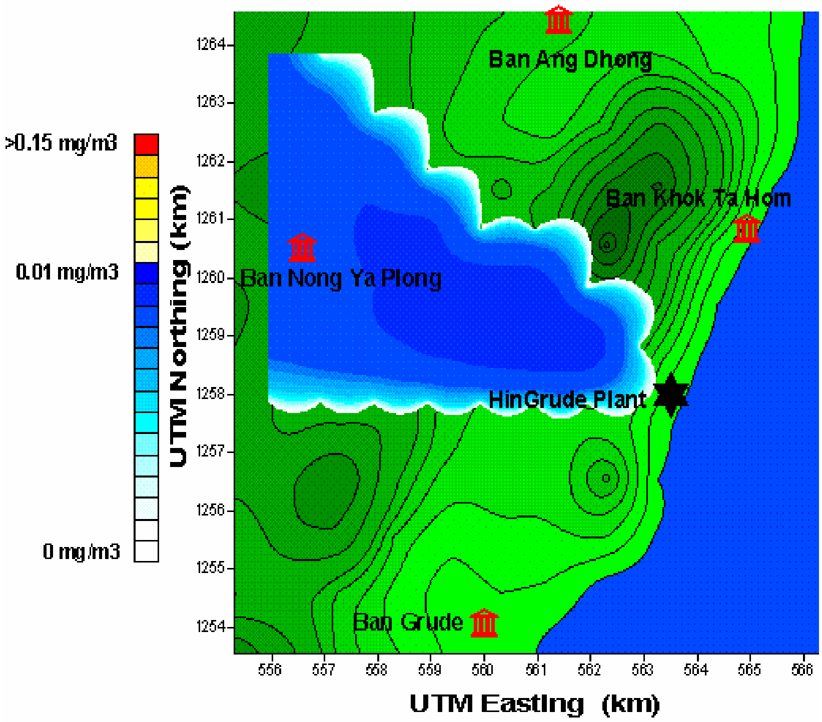
Appendix Figure J128 8th hour dispersion of PM_{10} in rainy season



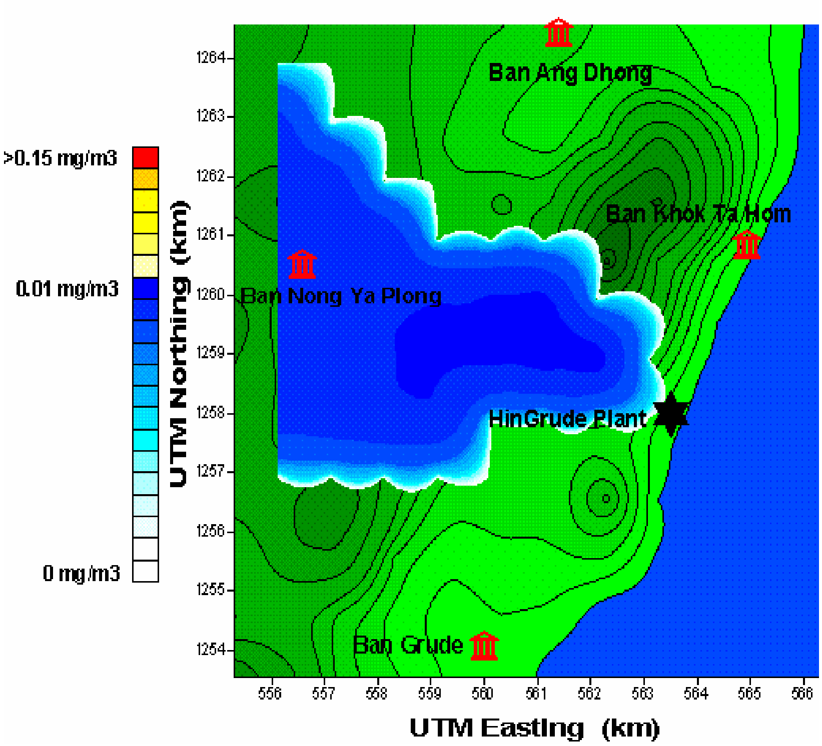
Appendix Figure J129 9th hour dispersion of PM_{10} in rainy season



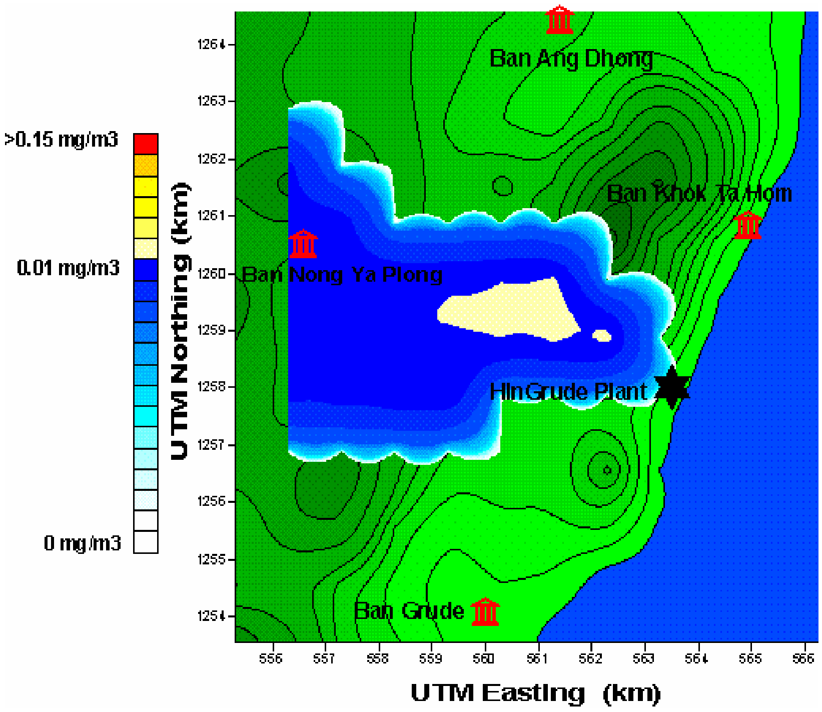
Appendix Figure J130 10th hour dispersion of PM_{10} in rainy season



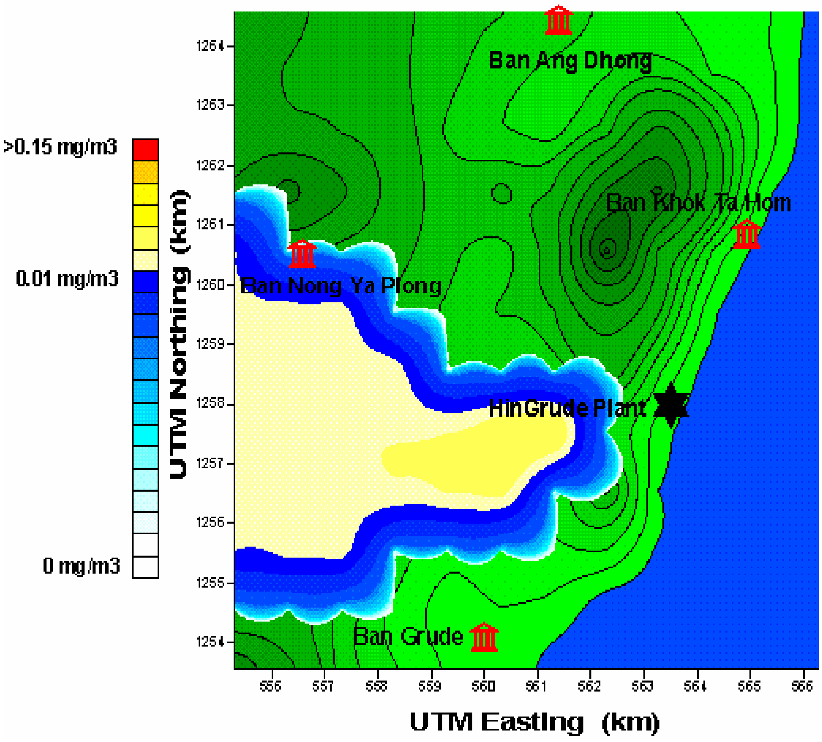
Appendix Figure J131 11th hour dispersion of PM_{10} in rainy season



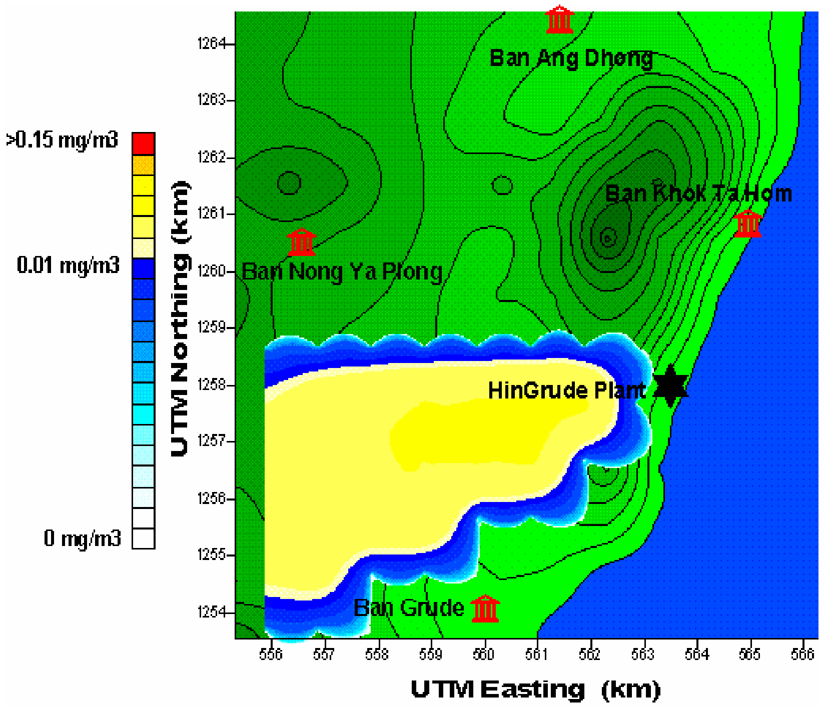
Appendix Figure J132 12th hour dispersion of PM_{10} in rainy season



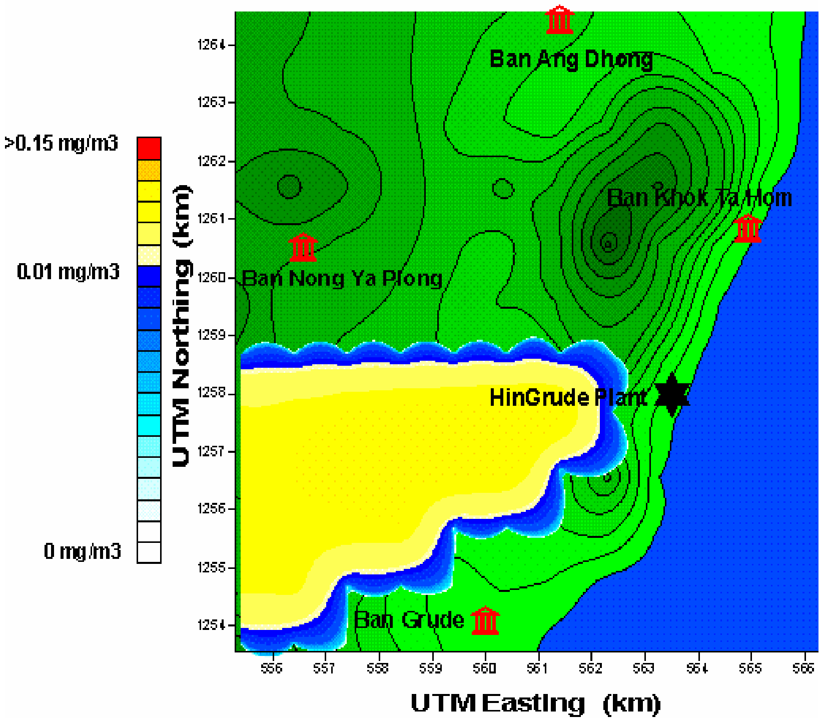
Appendix Figure J133 13th hour dispersion of PM_{10} in rainy season



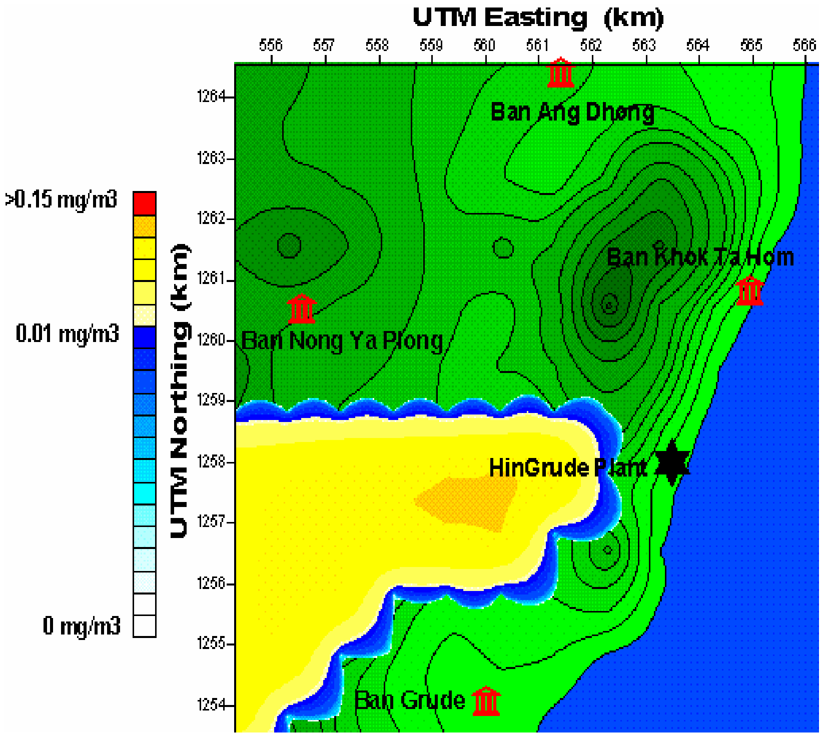
Appendix Figure J134 14th hour dispersion of PM_{10} in rainy season



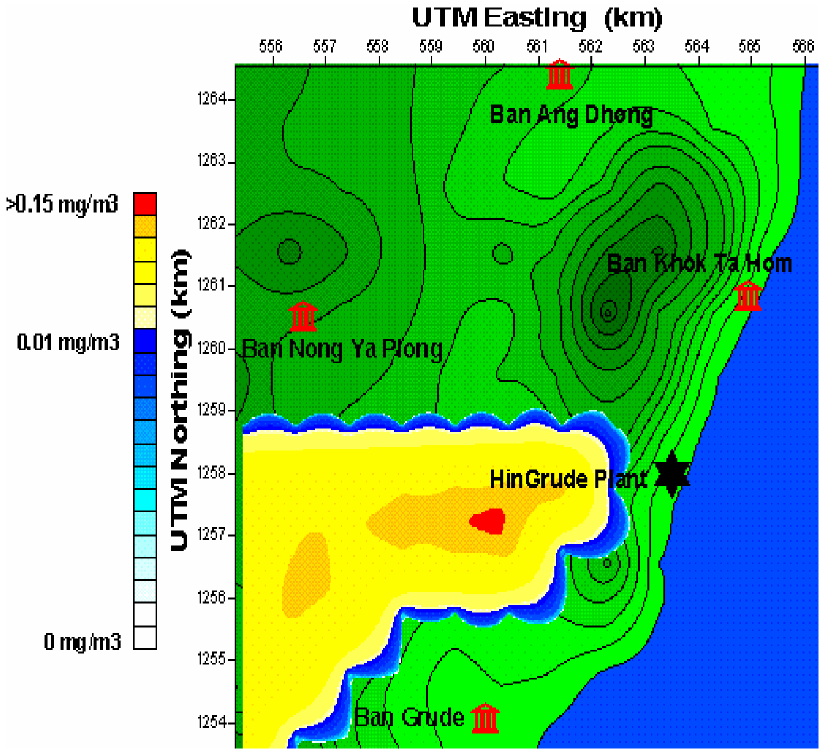
Appendix Figure J135 15th hour dispersion of PM_{10} in rainy season



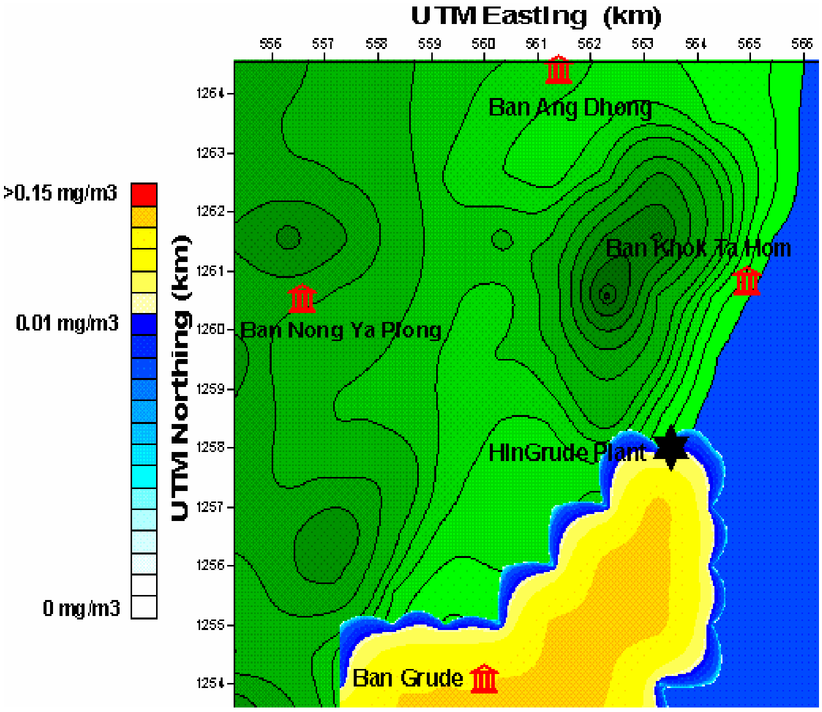
Appendix Figure J136 16th hour dispersion of PM_{10} in rainy season



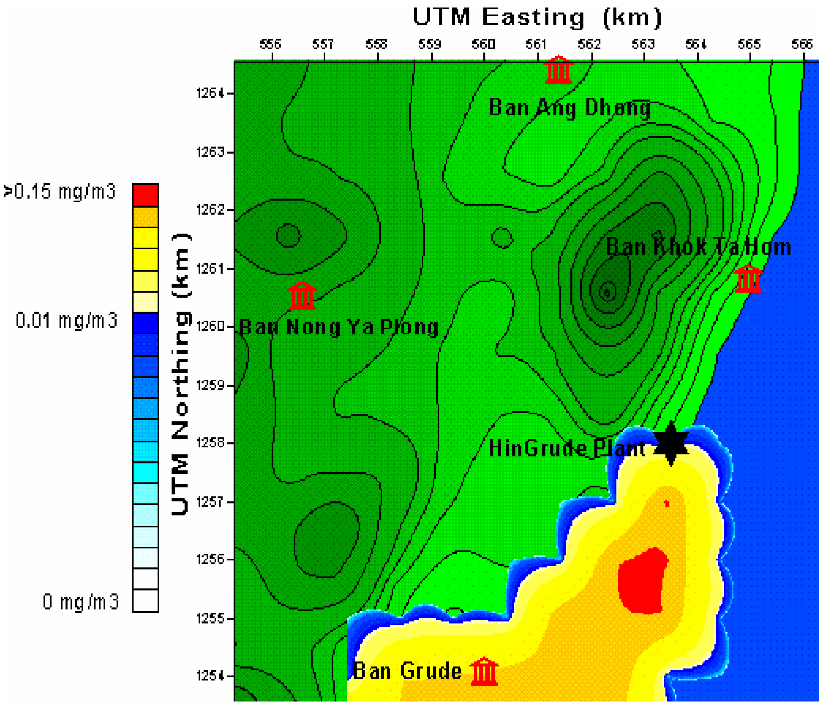
Appendix Figure J137 17th hour dispersion of PM_{10} in rainy season



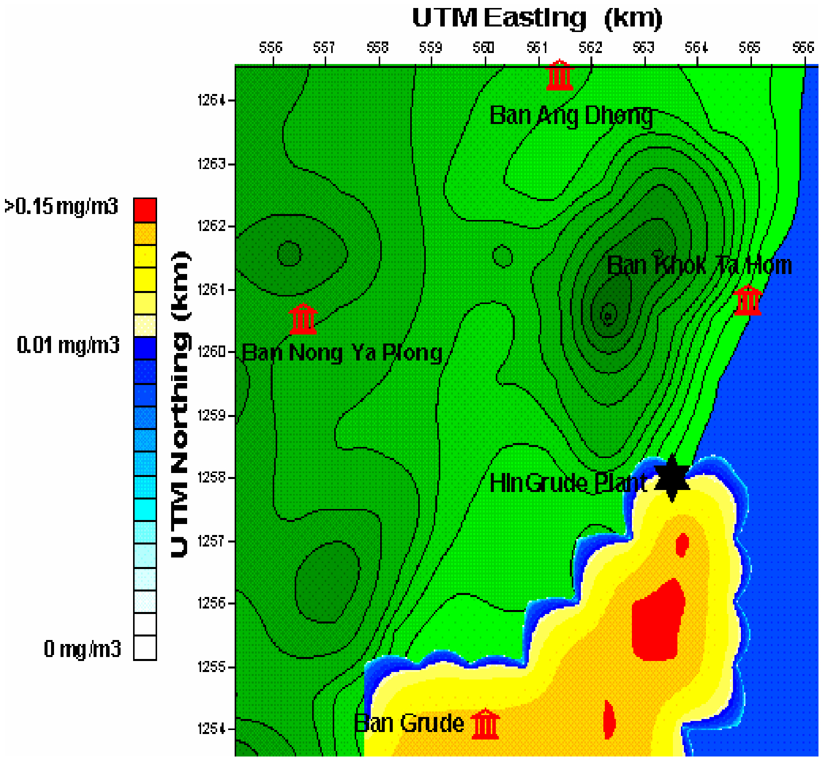
Appendix Figure J138 18th hour dispersion of PM_{10} in rainy season



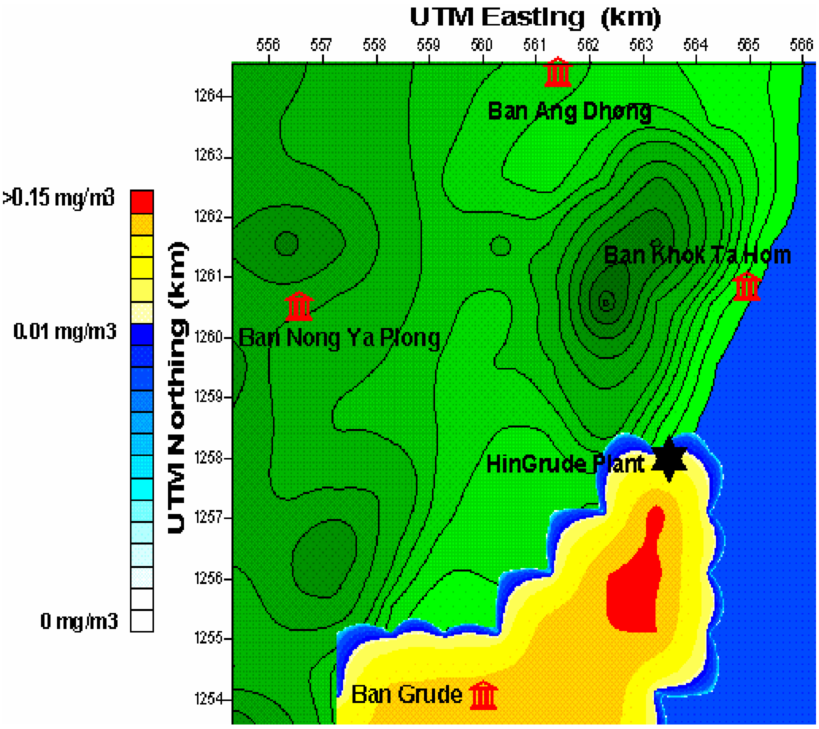
Appendix Figure J139 19th hour dispersion of PM_{10} in rainy season



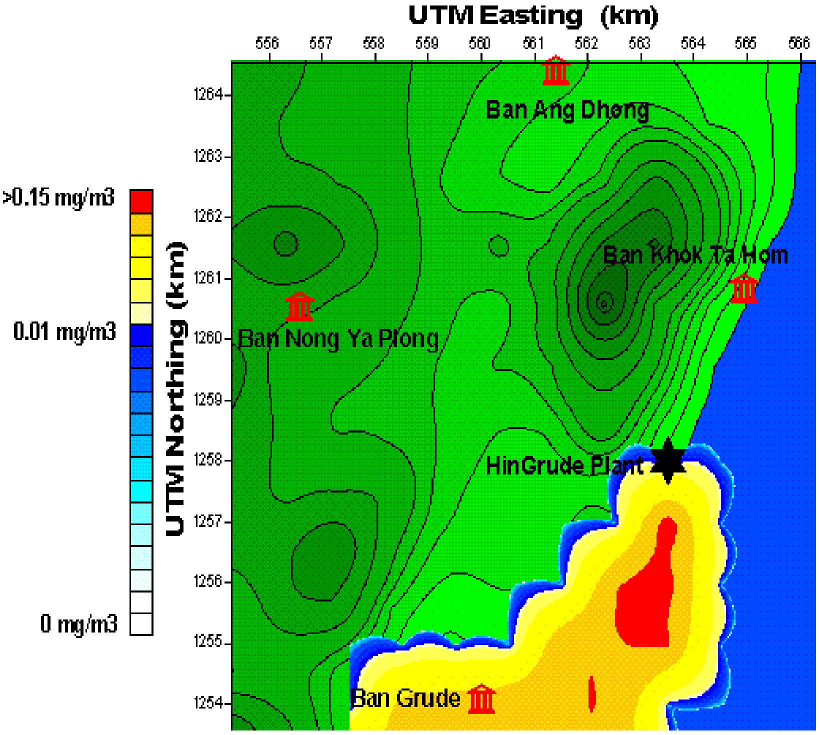
Appendix Figure J140 20th hour dispersion of PM_{10} in rainy season



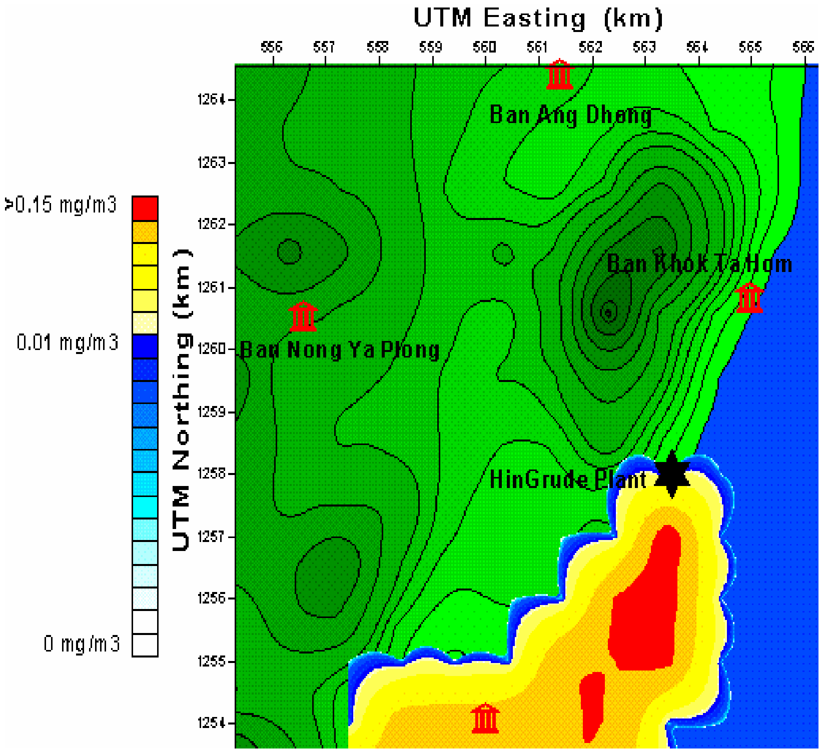
Appendix Figure J141 21st hour dispersion of PM_{10} in rainy season



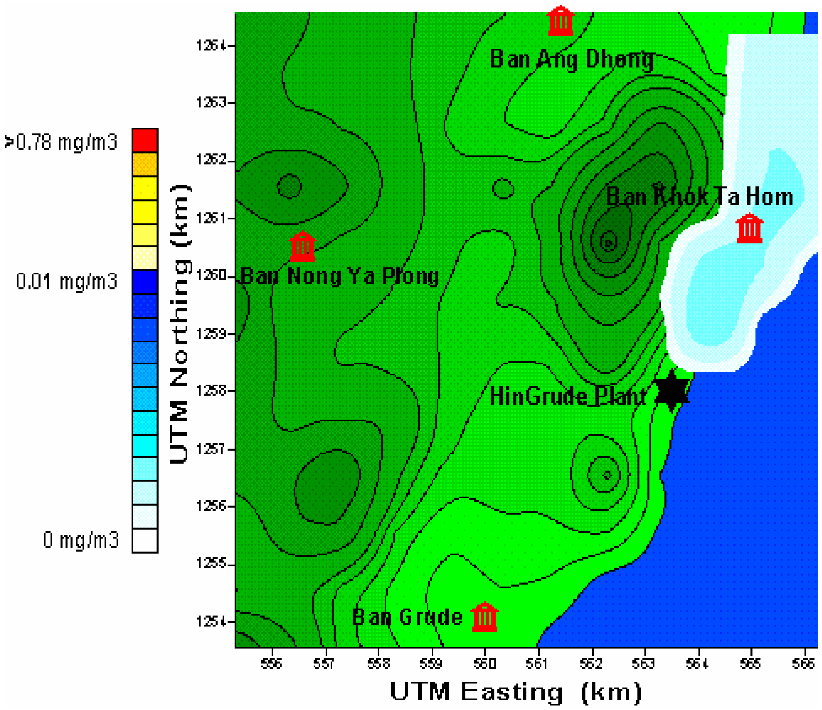
Appendix Figure J142 22nd hour dispersion of PM_{10} in rainy season



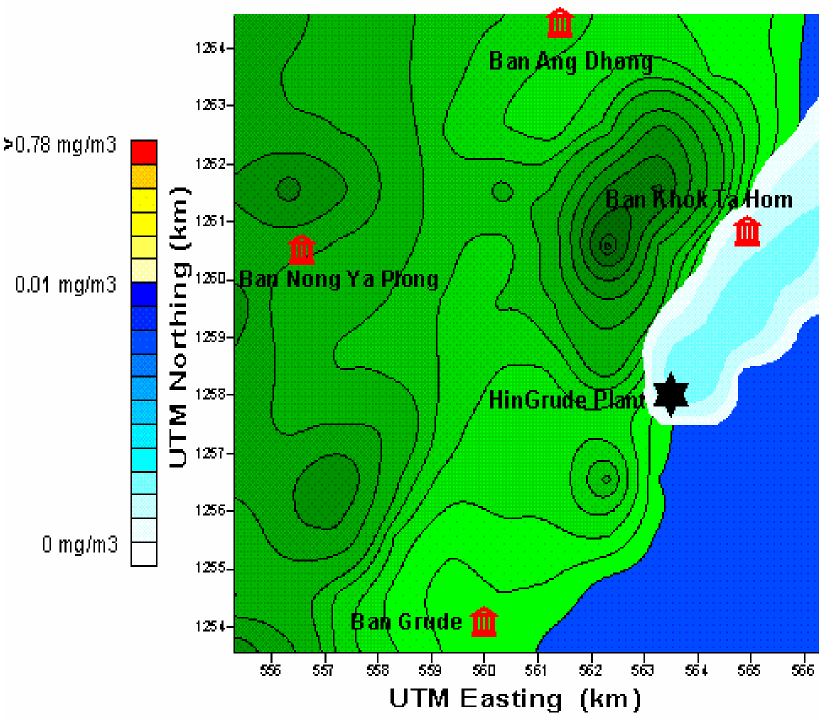
Appendix Figure J143 23rd hour dispersion of PM_{10} in rainy season



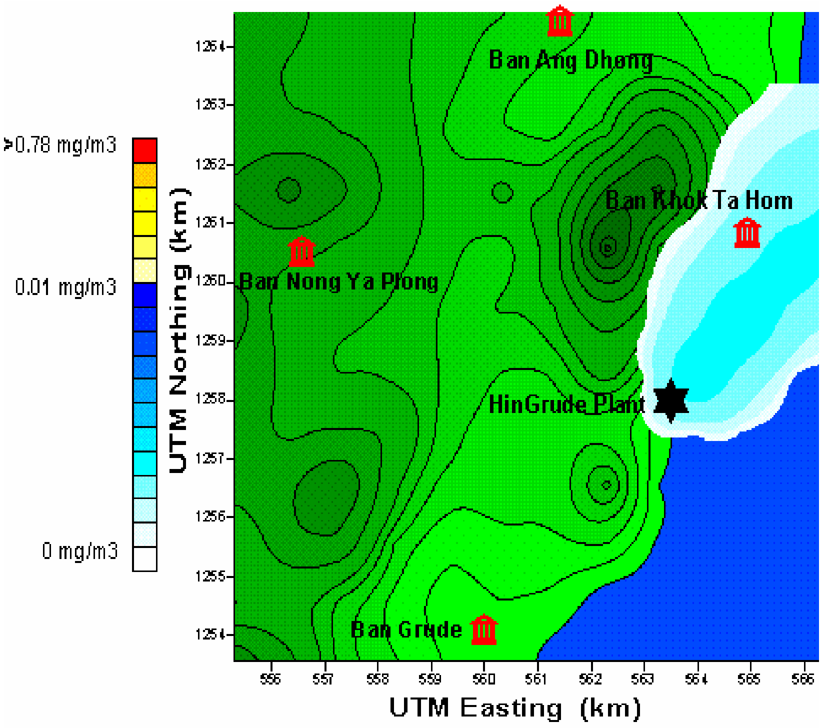
Appendix Figure J144 24th hour dispersion of PM_{10} in rainy season



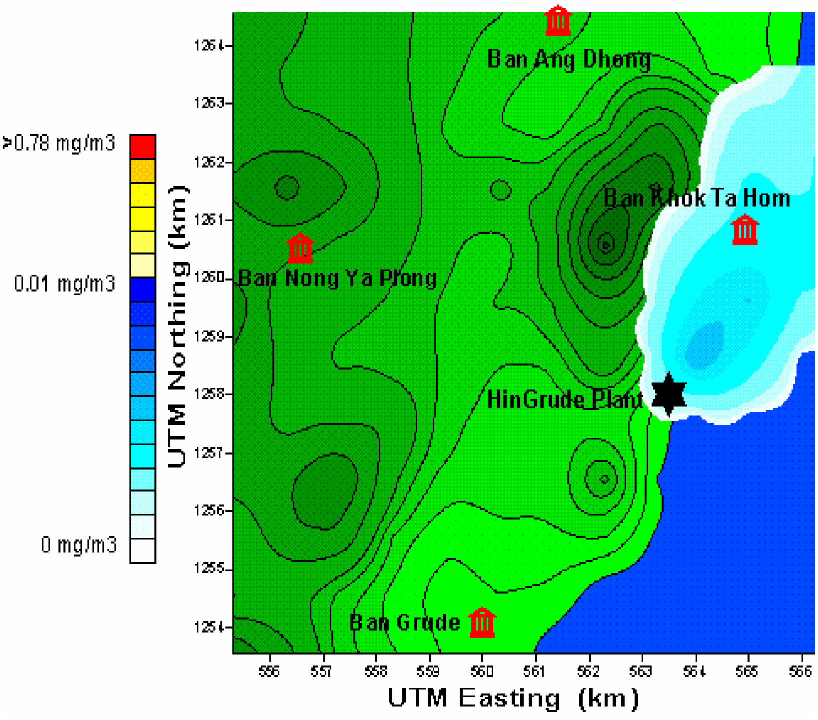
Appendix Figure J145 1st hour dispersion of SO_2 in winter



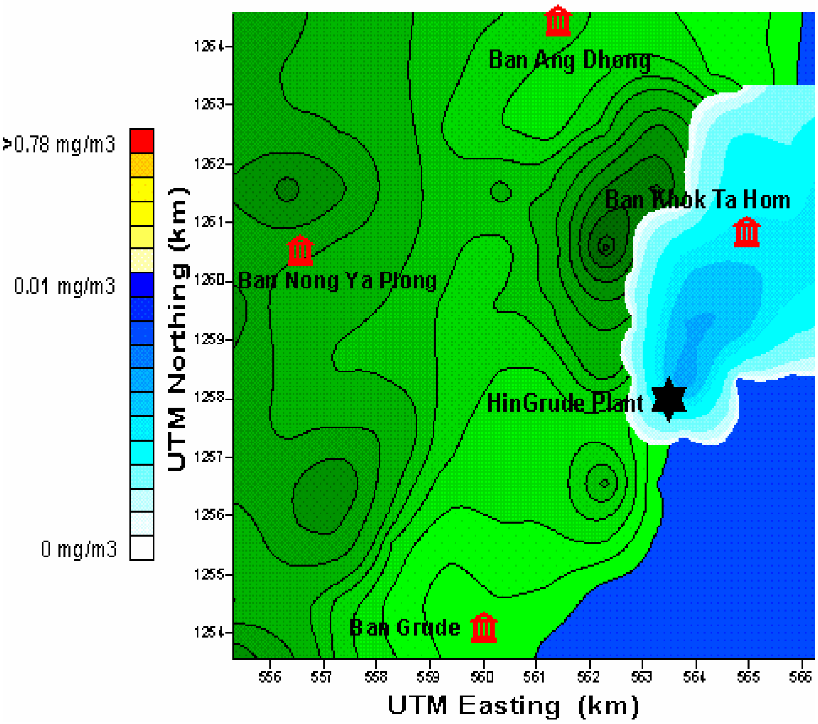
Appendix Figure J146 2nd hour dispersion of SO_2 in winter



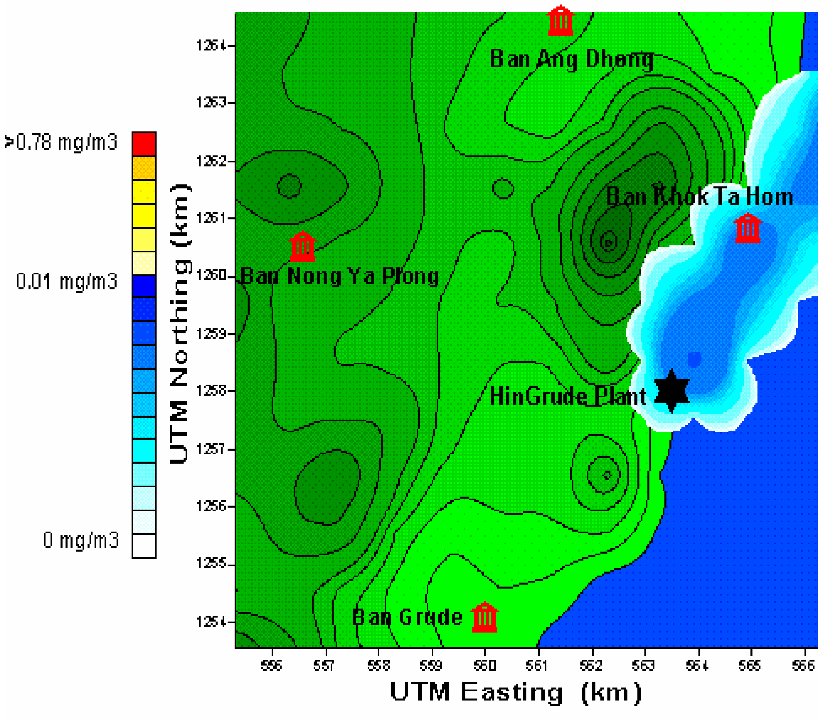
Appendix Figure J147 3rd hour dispersion of SO_2 in winter



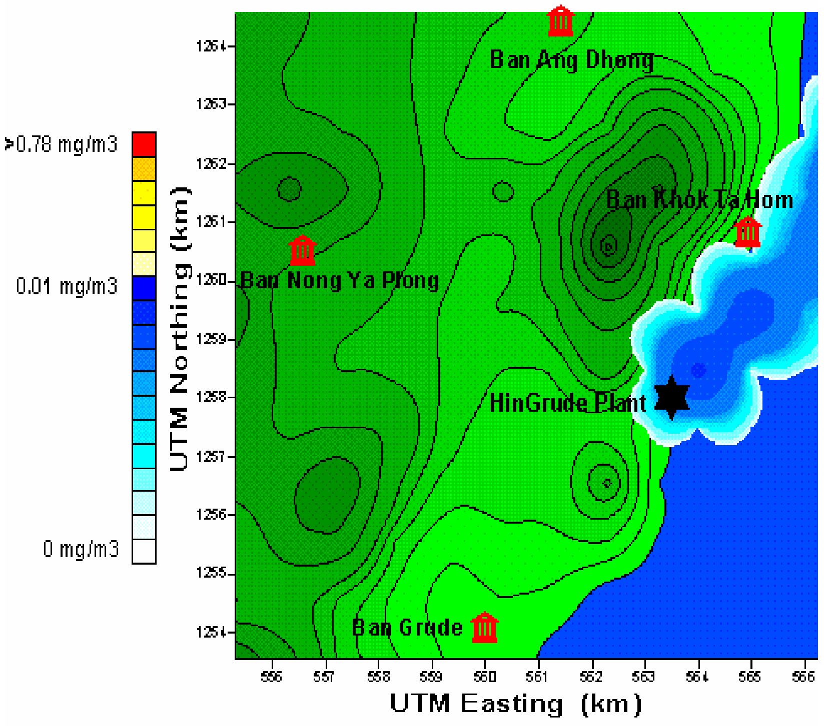
Appendix Figure J148 4th hour dispersion of SO_2 in winter



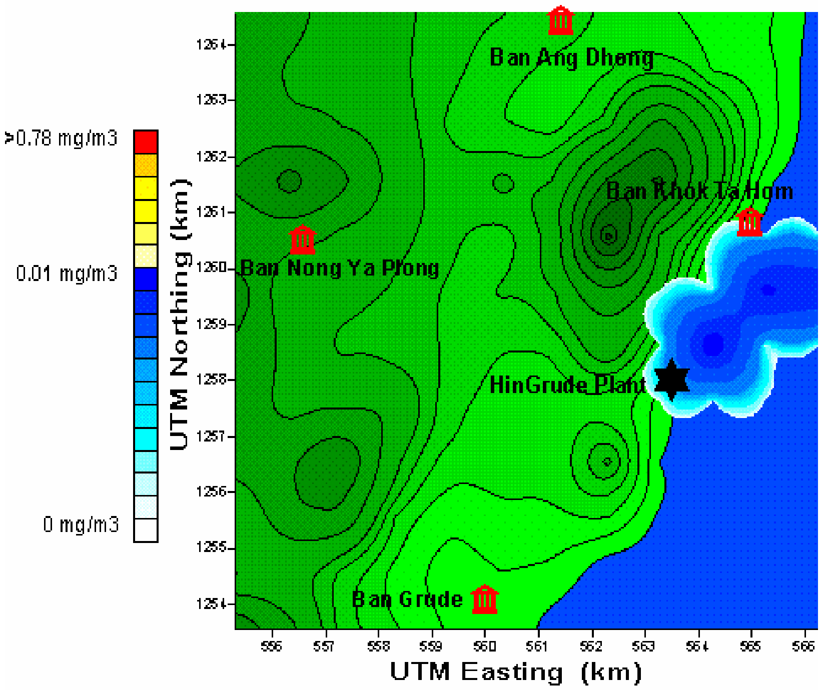
Appendix Figure J149 5th hour dispersion of SO_2 in winter



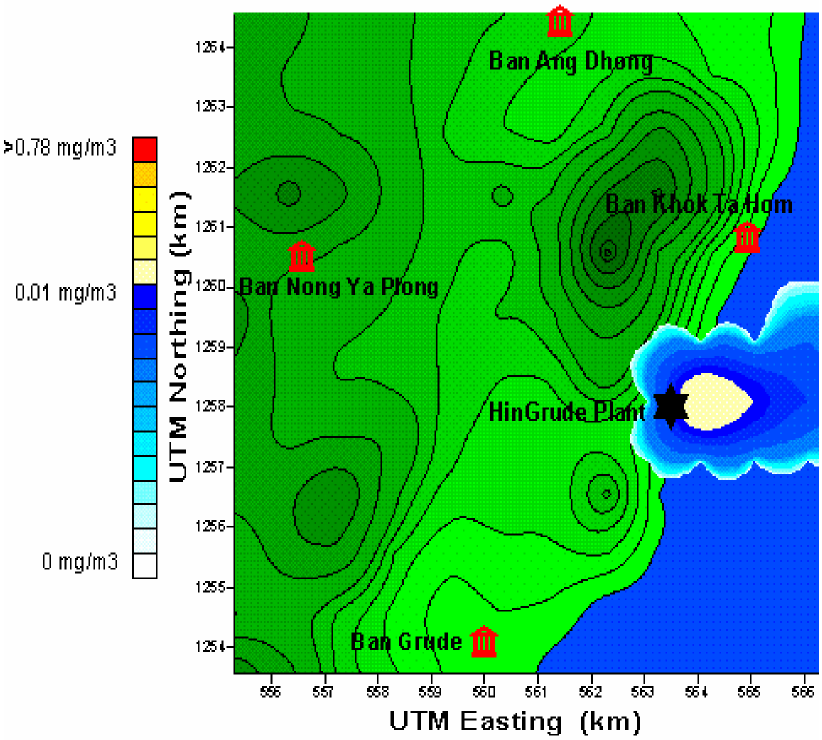
Appendix Figure J150 6th hour dispersion of SO_2 in winter



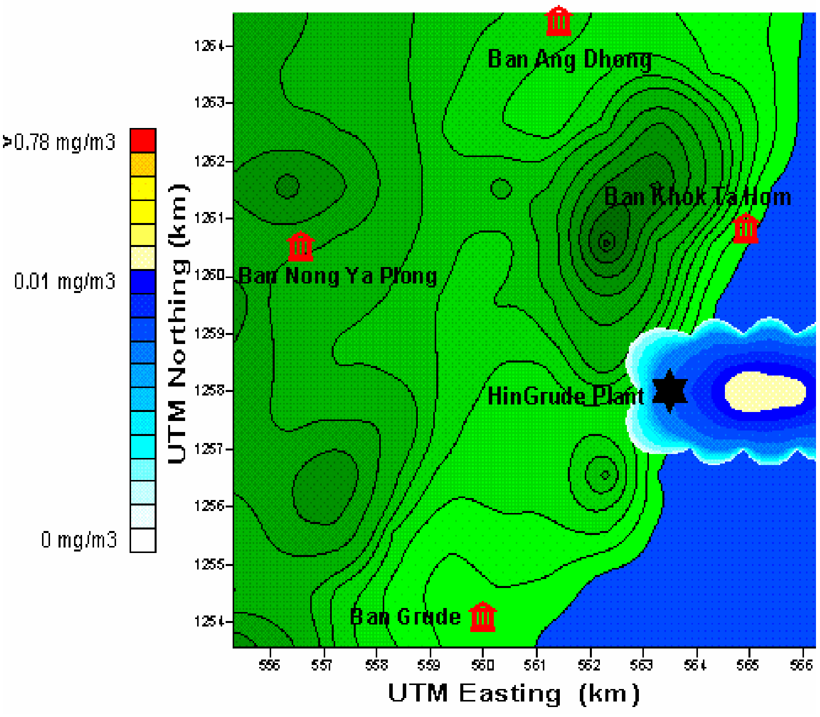
Appendix Figure J151 7th hour dispersion of SO_2 in winter



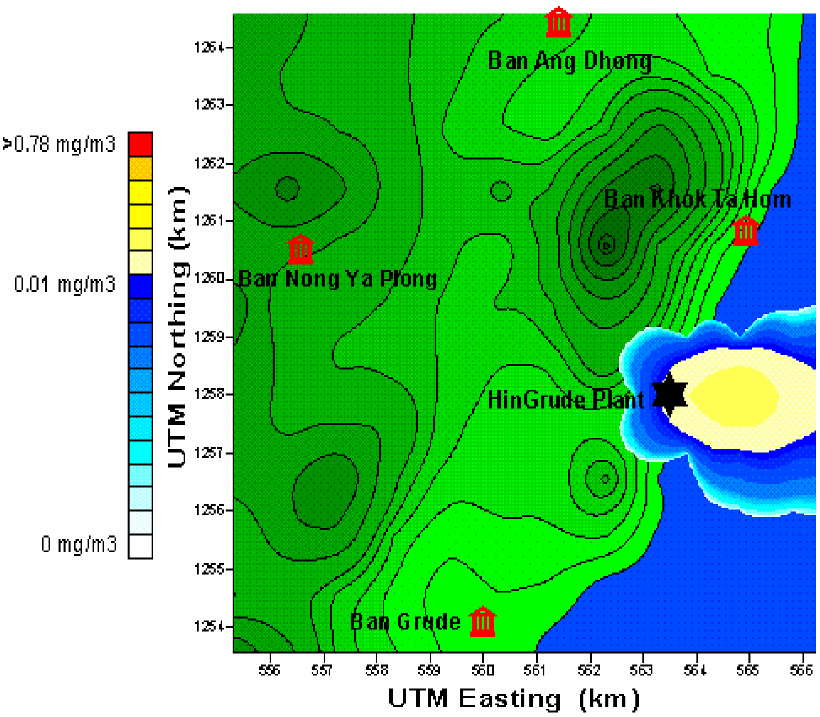
Appendix Figure J152 8th hour dispersion of SO_2 in winter



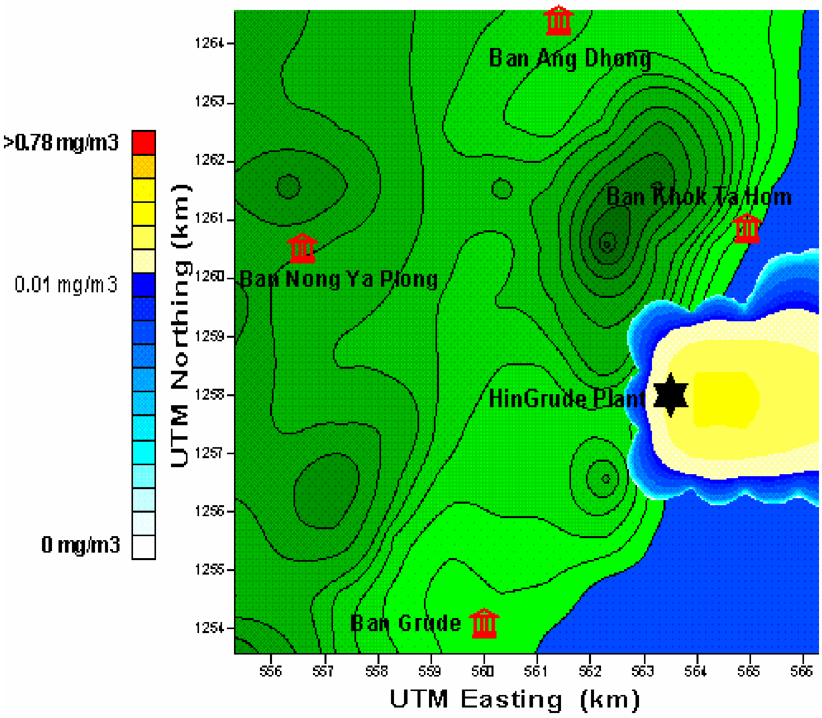
Appendix Figure J153 9th hour dispersion of SO_2 in winter



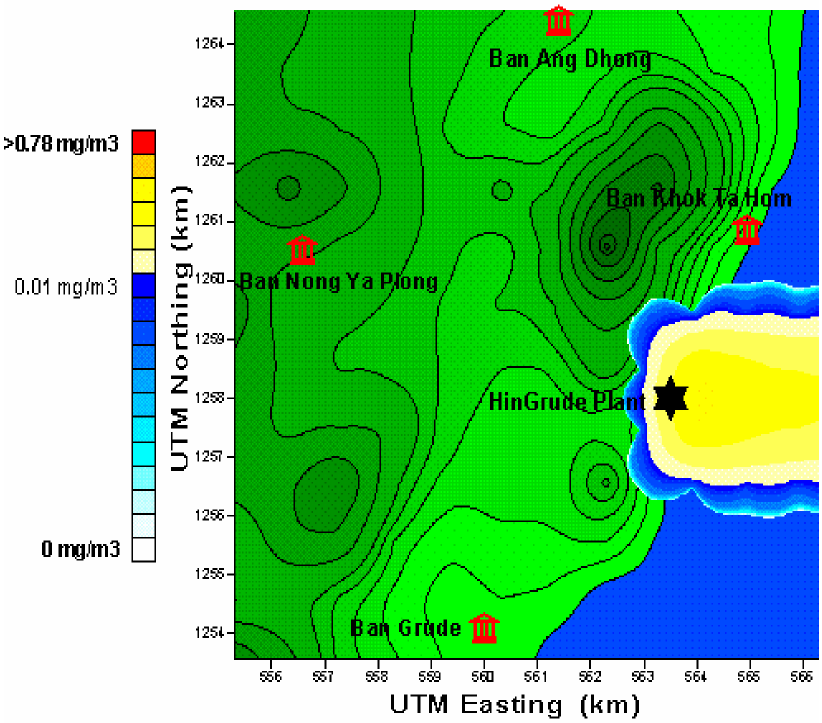
Appendix Figure J154 10th hour dispersion of SO_2 in winter



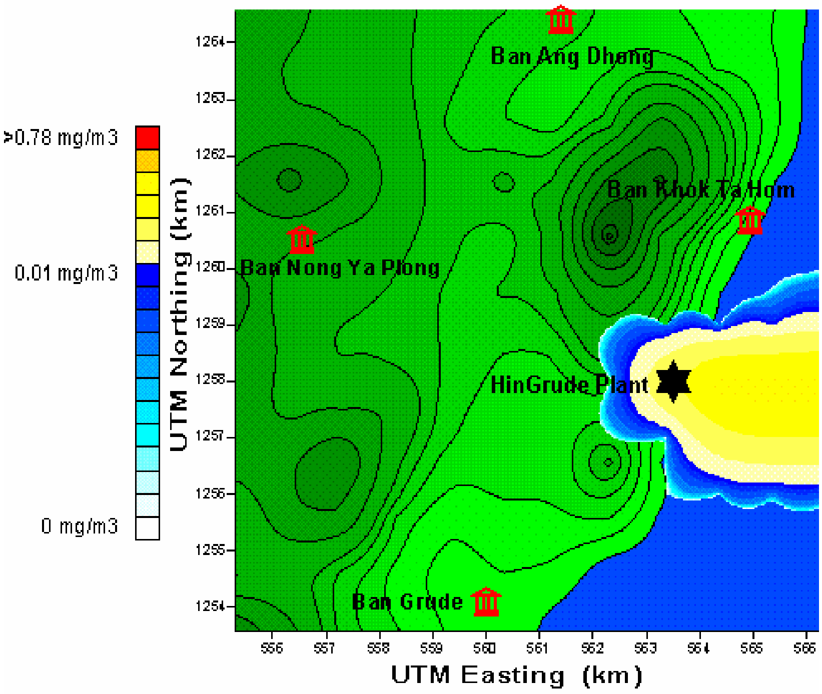
Appendix Figure J155 11th hour dispersion of SO_2 in winter



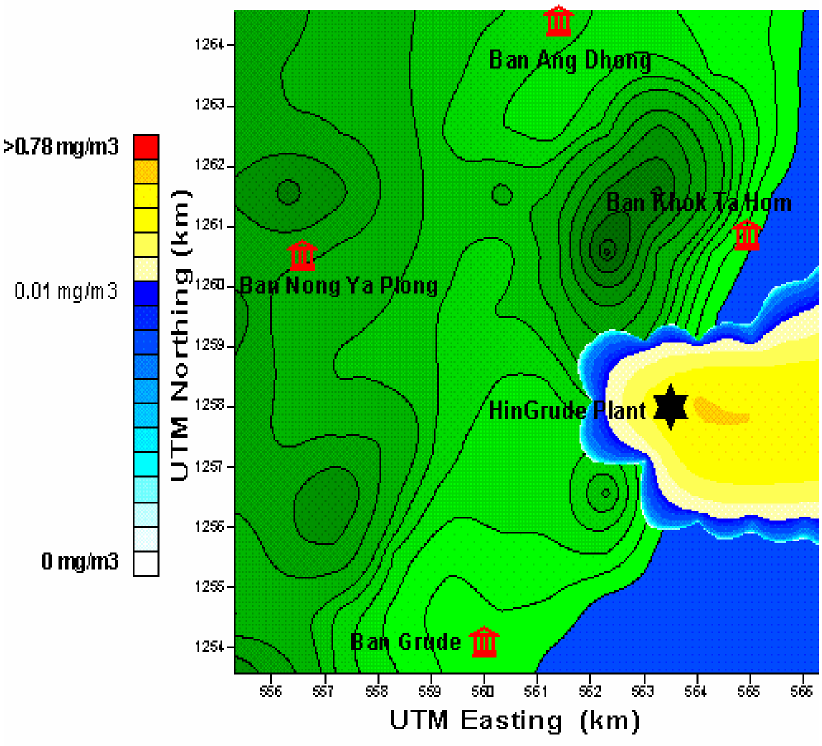
Appendix Figure J156 12th hour dispersion of SO_2 in winter



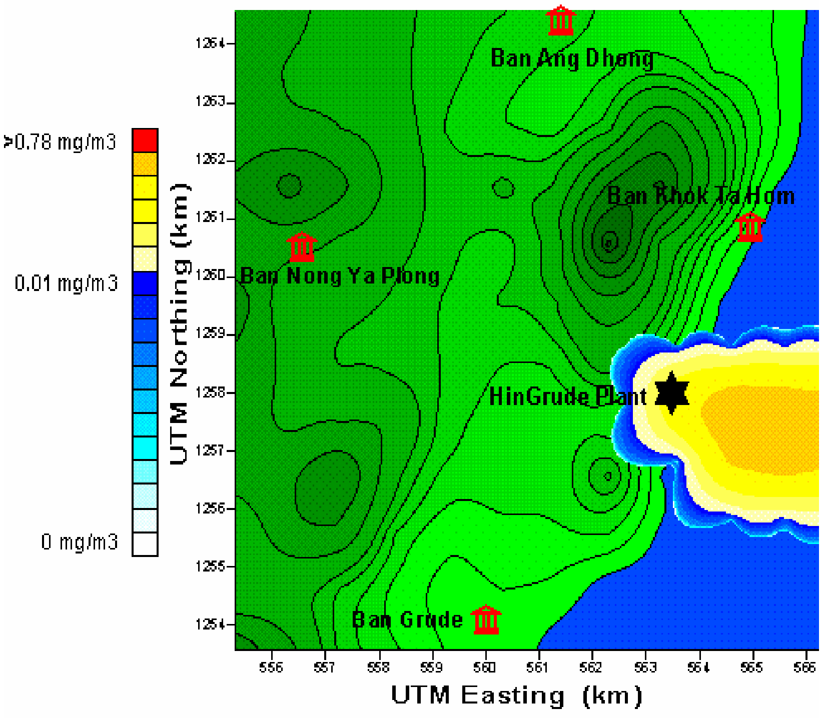
Appendix Figure J157 13th hour dispersion of SO_2 in winter



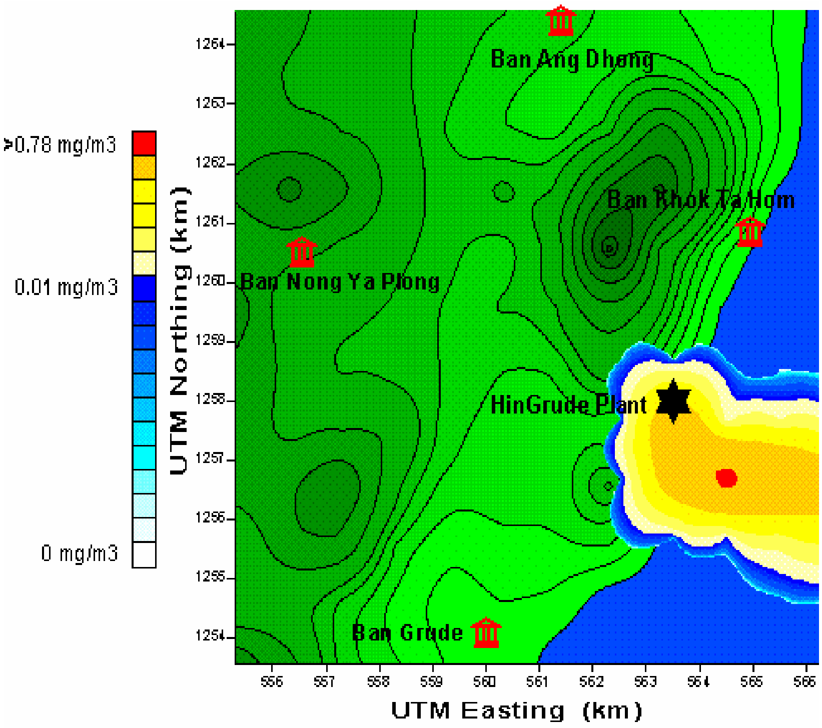
Appendix Figure J158 14th hour dispersion of SO_2 in winter



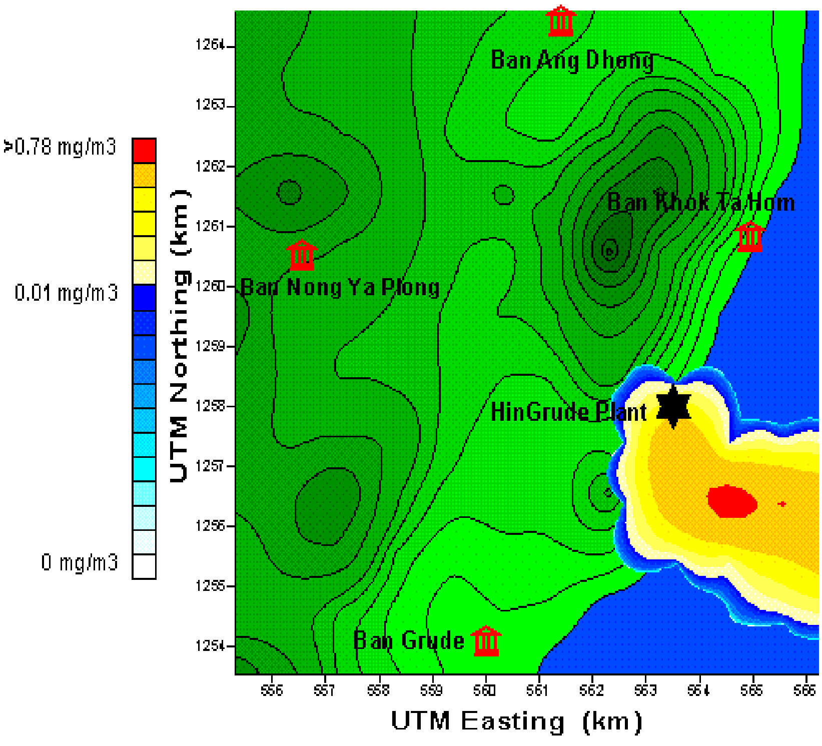
Appendix Figure J159 15th hour dispersion of SO_2 in winter



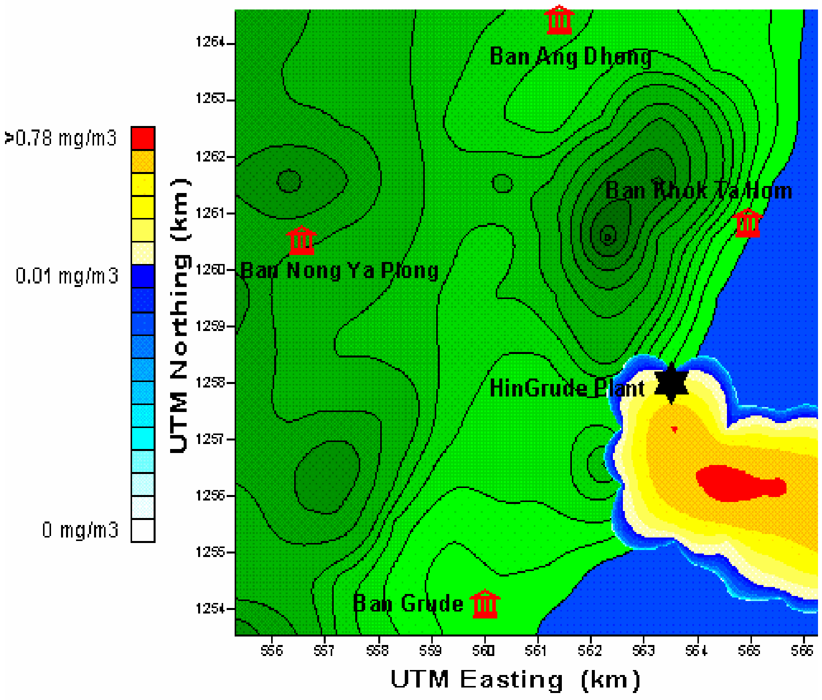
Appendix Figure J160 16th hour dispersion of SO_2 in winter



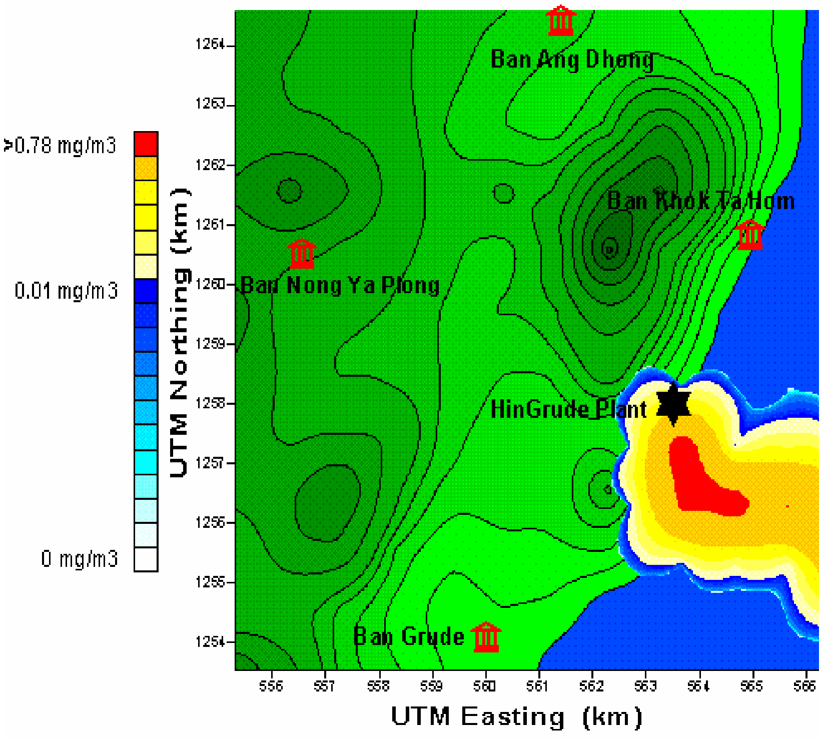
Appendix Figure J161 17th hour dispersion of SO_2 in winter



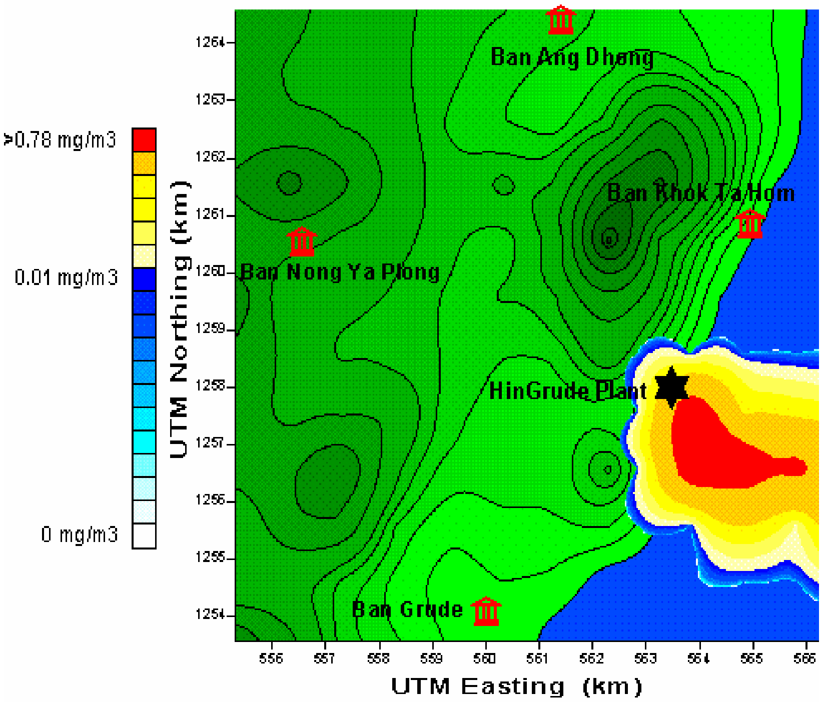
Appendix Figure J162 18th hour dispersion of SO_2 in winter



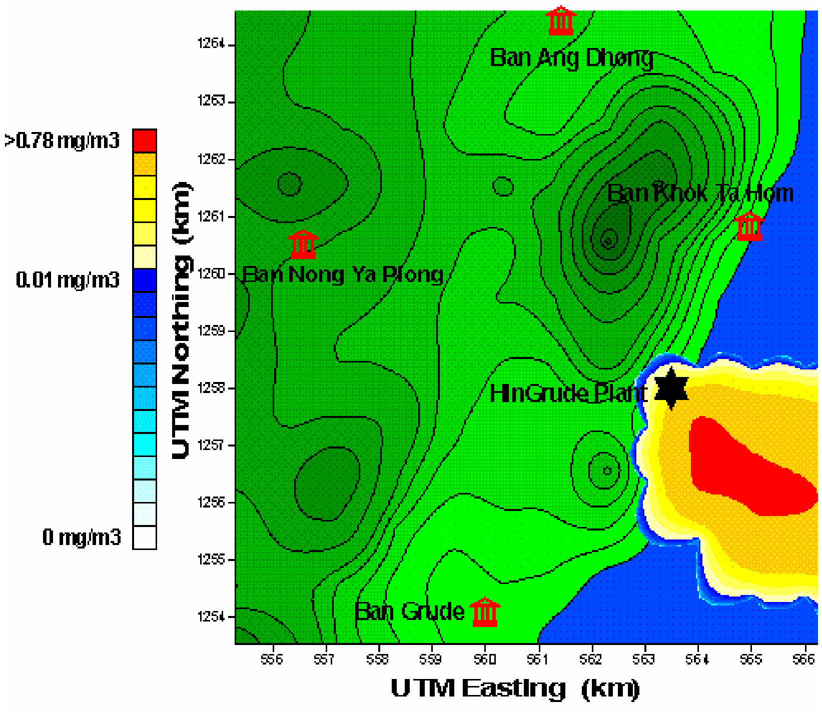
Appendix Figure J163 19th hour dispersion of SO_2 in winter



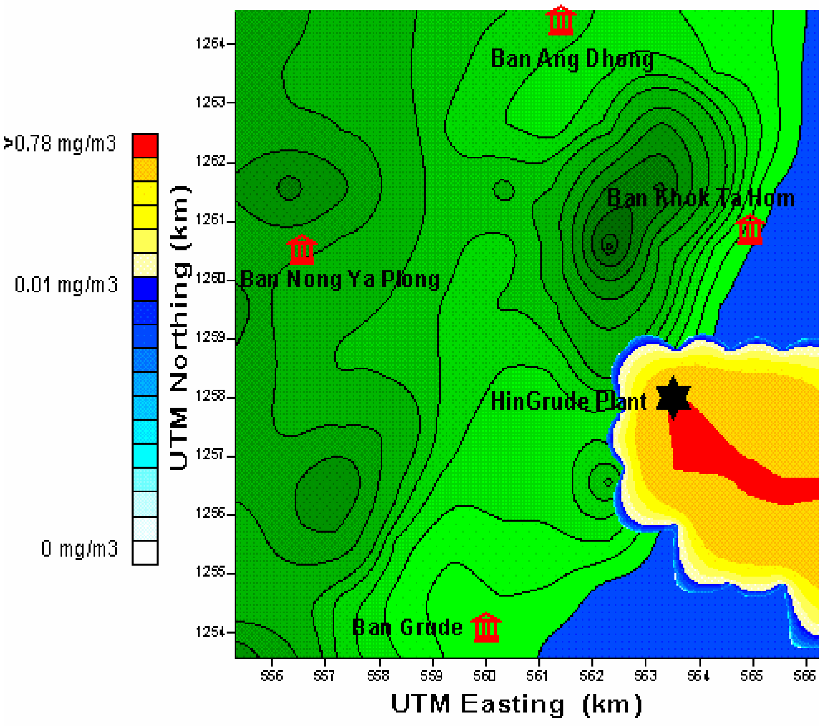
Appendix Figure J164 20th hour dispersion of SO_2 in winter



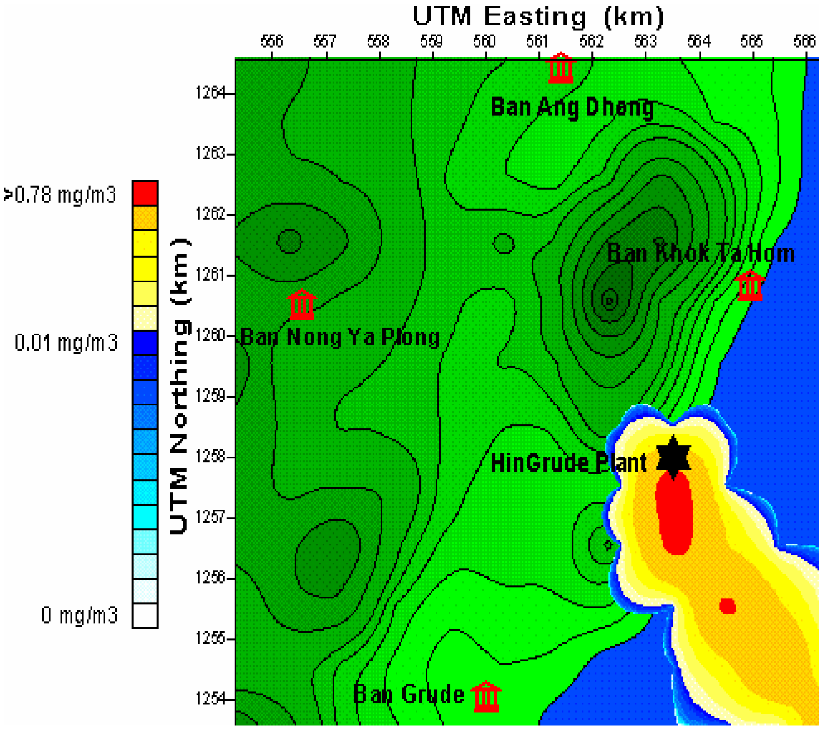
Appendix Figure J165 21st hour dispersion of SO_2 in winter



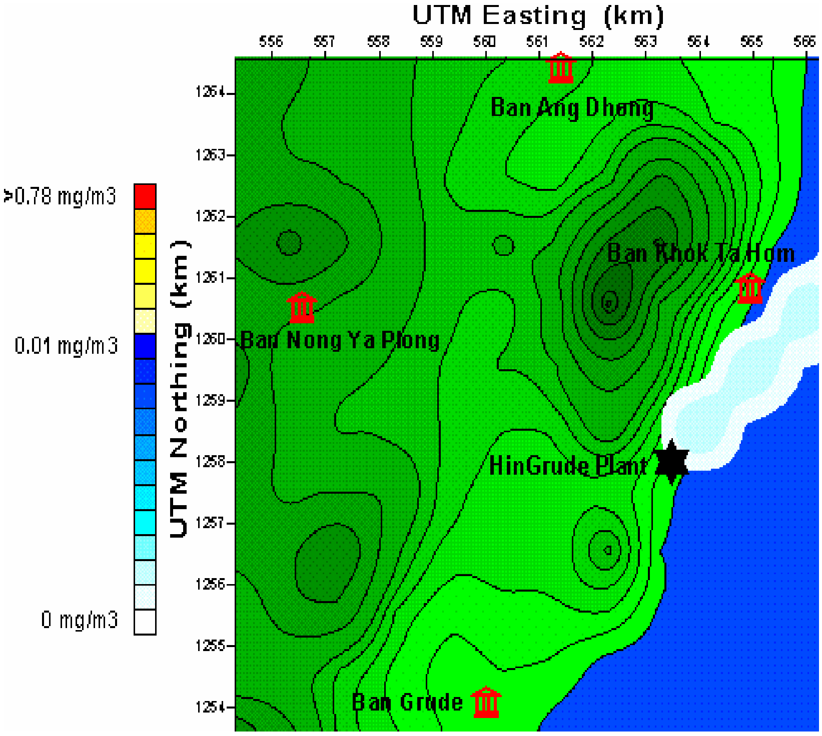
Appendix Figure J166 22nd hour dispersion of SO_2 in winter



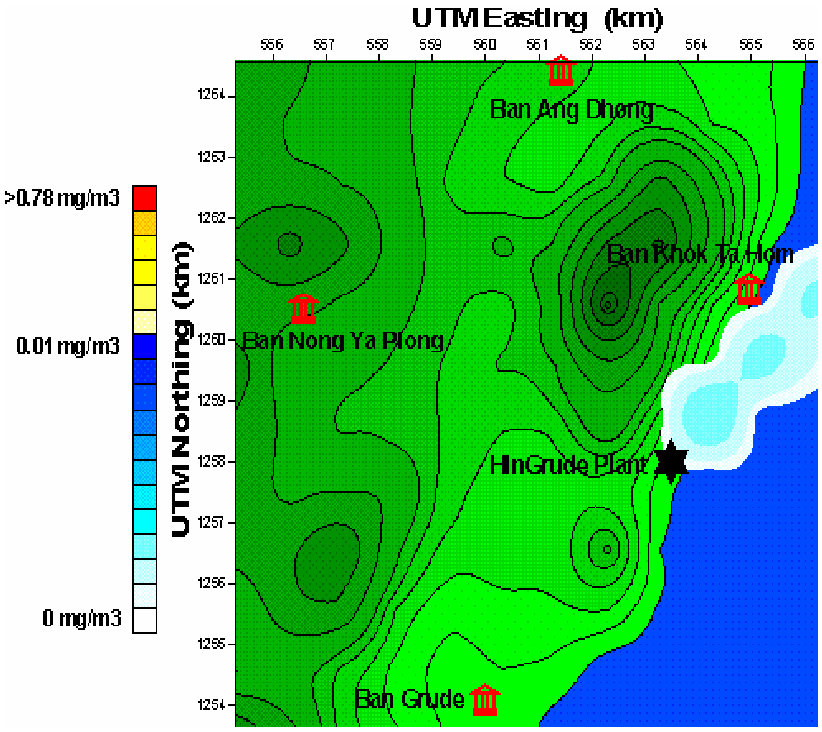
Appendix Figure J167 23rd hour dispersion of SO_2 in winter



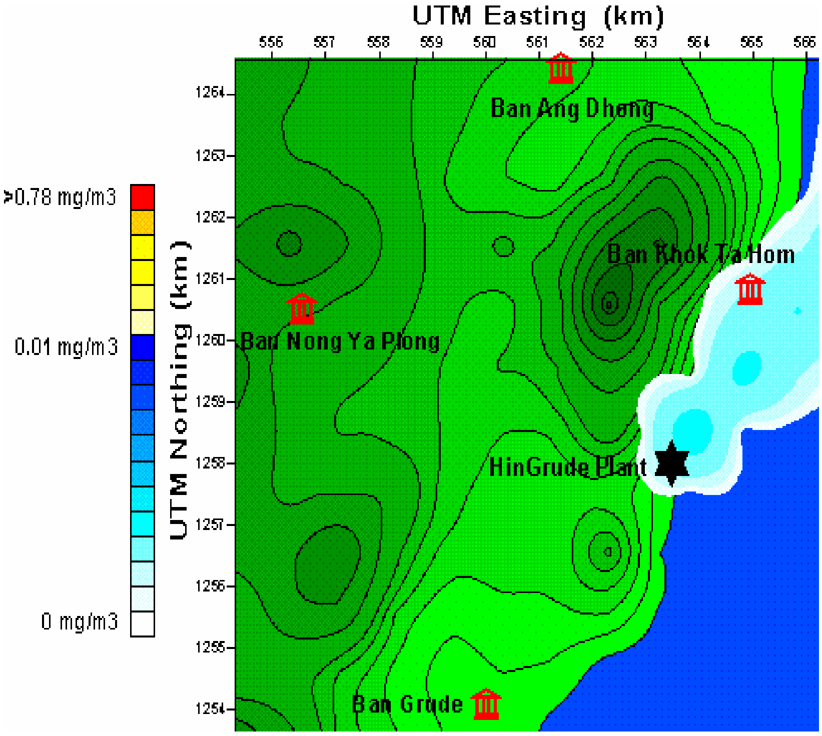
Appendix Figure J168 24th hour dispersion of SO_2 in winter



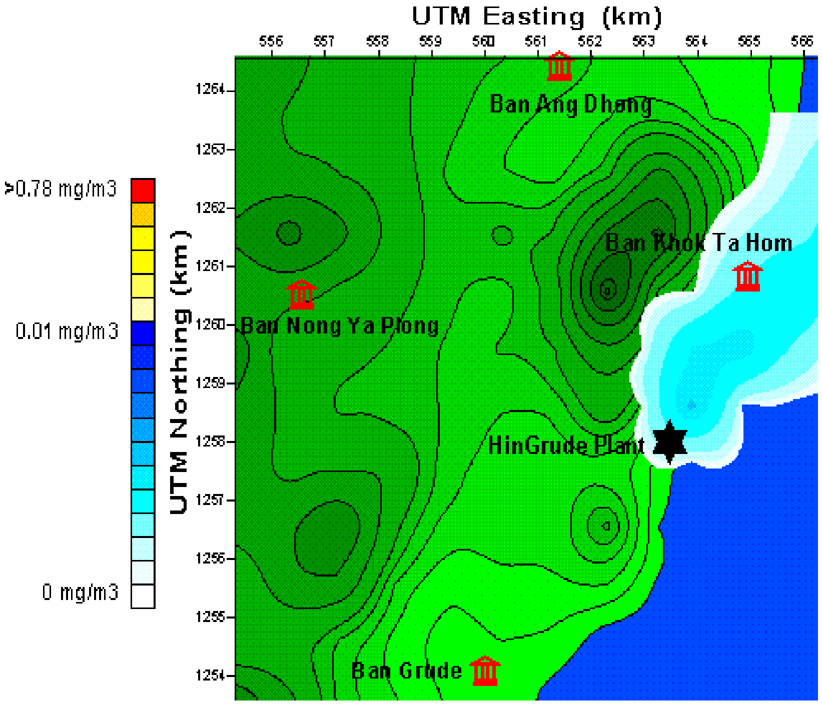
Appendix Figure J169 1st hour dispersion of SO_2 in summer



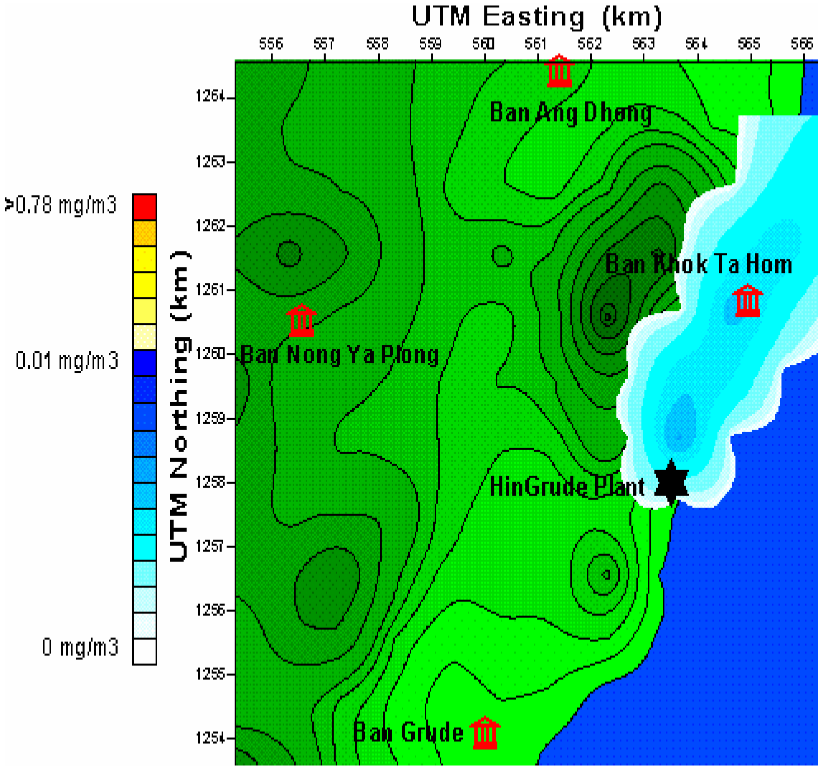
Appendix Figure J170 2nd hour dispersion of SO_2 in summer



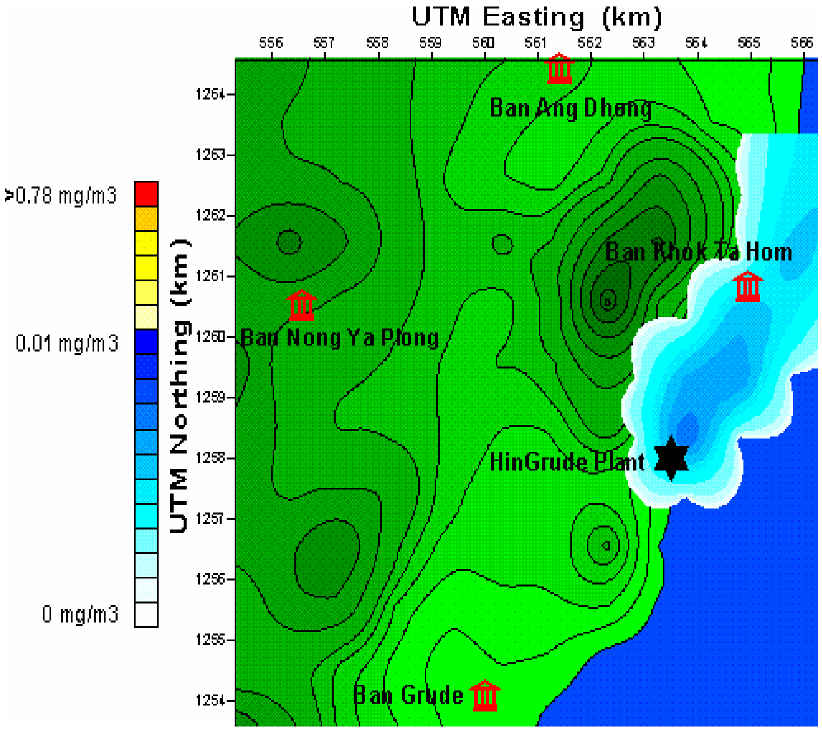
Appendix Figure J171 3rd hour dispersion of SO_2 in summer



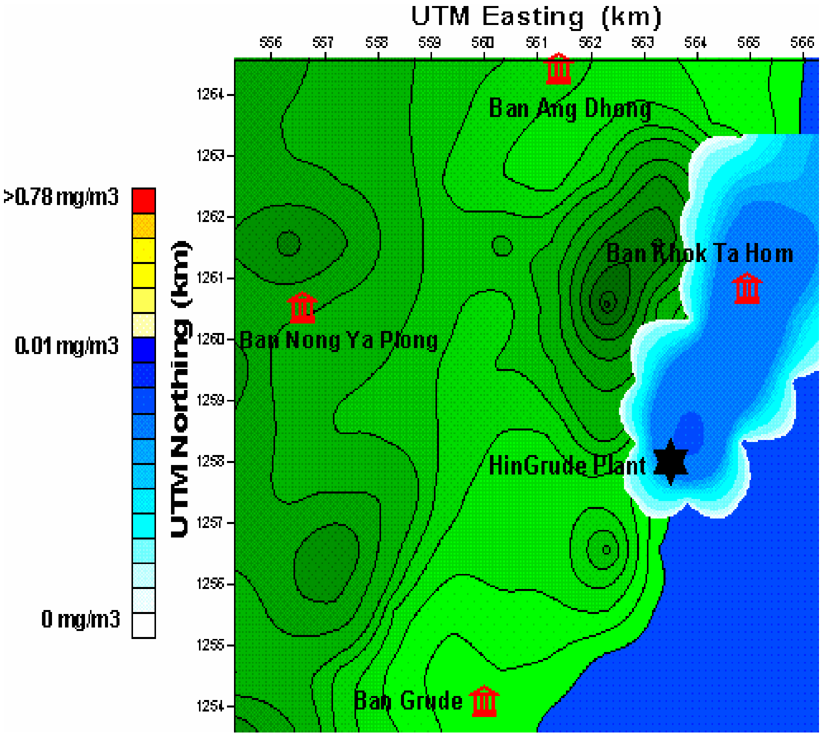
Appendix Figure J172 4th hour dispersion of SO_2 in summer



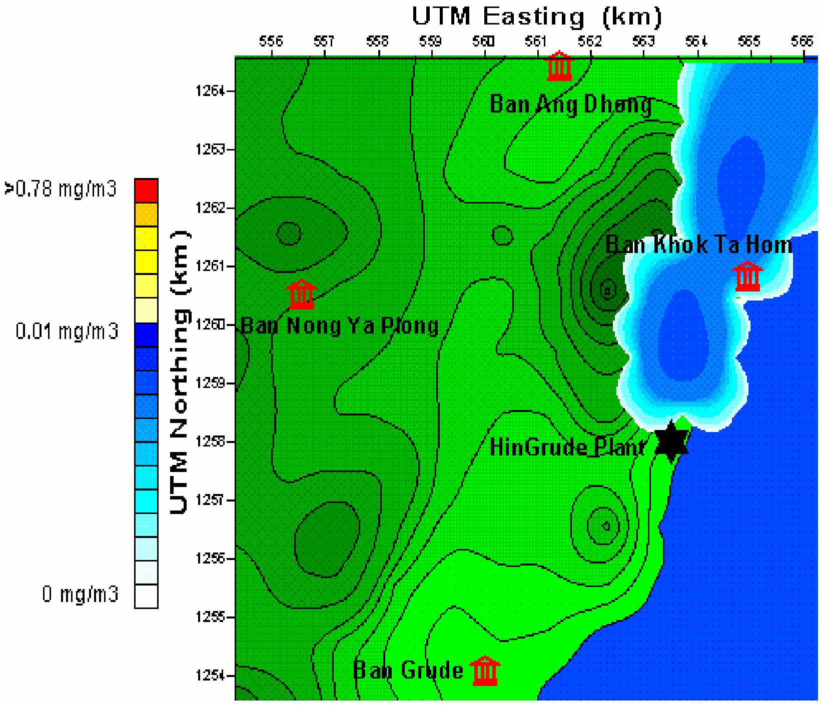
Appendix Figure J173 5th hour dispersion of SO_2 in summer



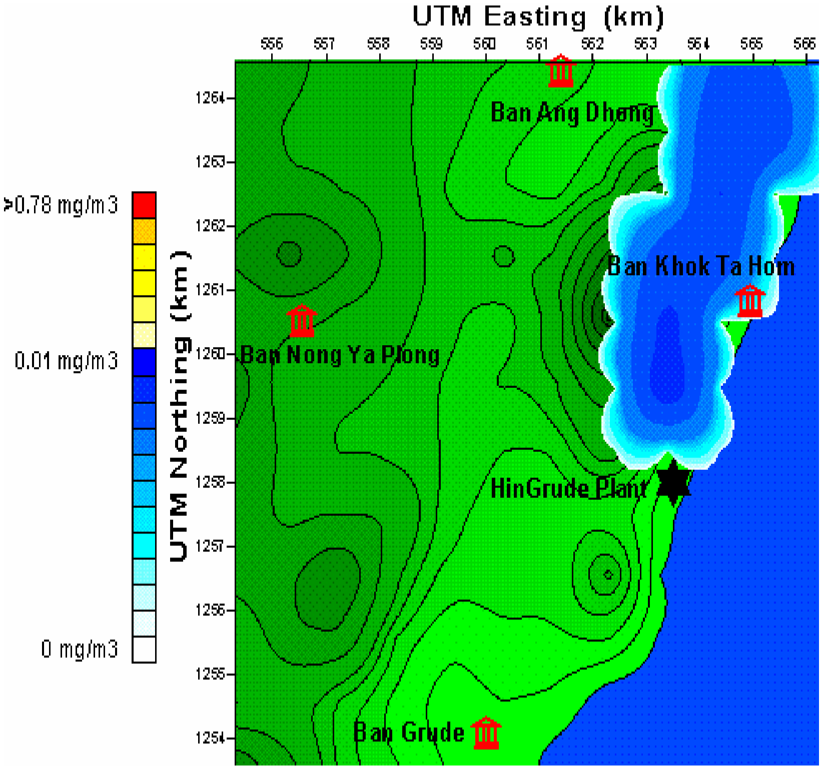
Appendix Figure J174 6th hour dispersion of SO_2 in summer



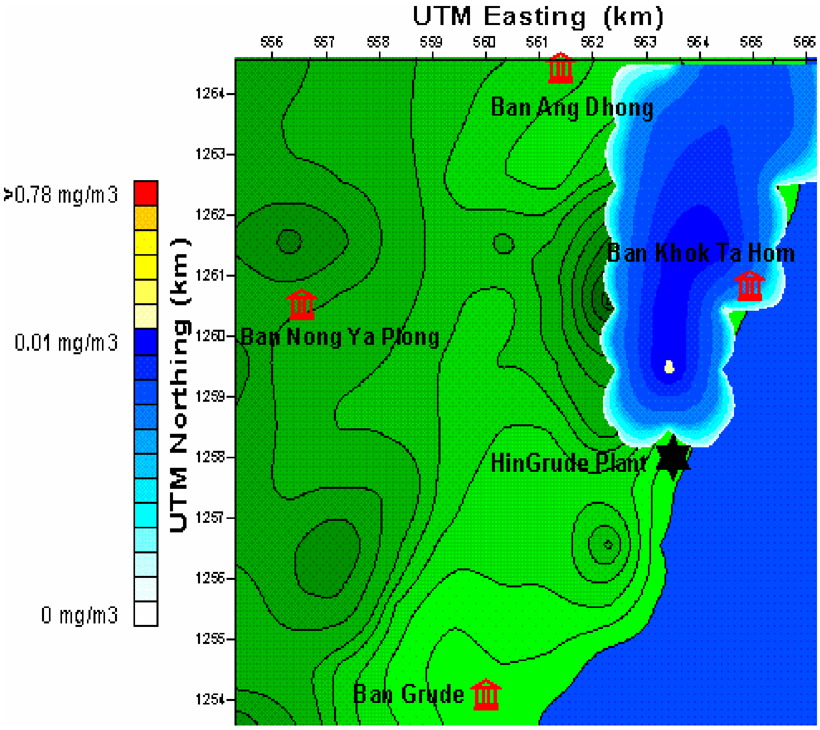
Appendix Figure J175 7th hour dispersion of SO_2 in summer



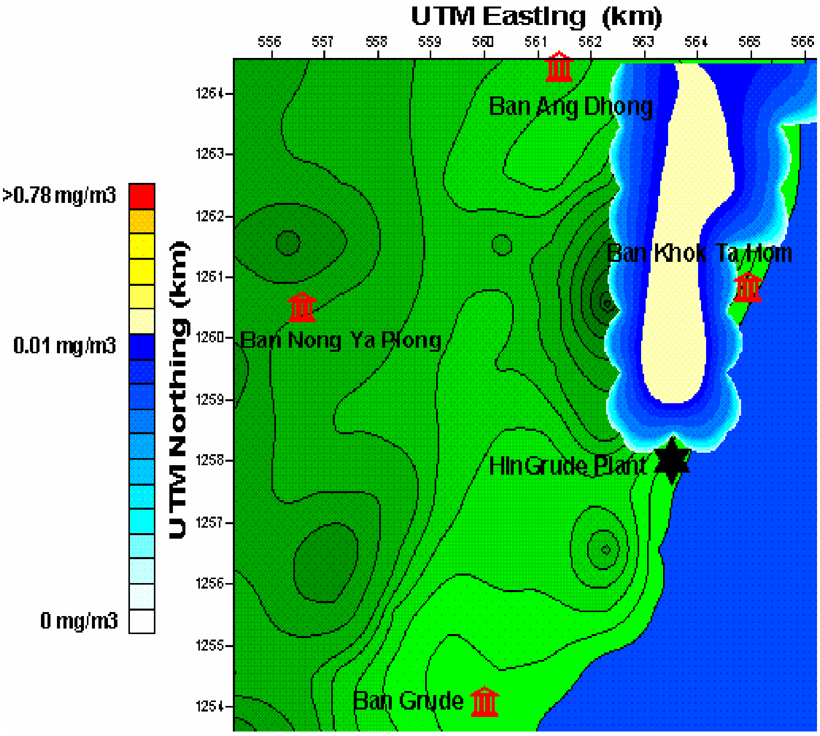
Appendix Figure J176 8th hour dispersion of SO_2 in summer



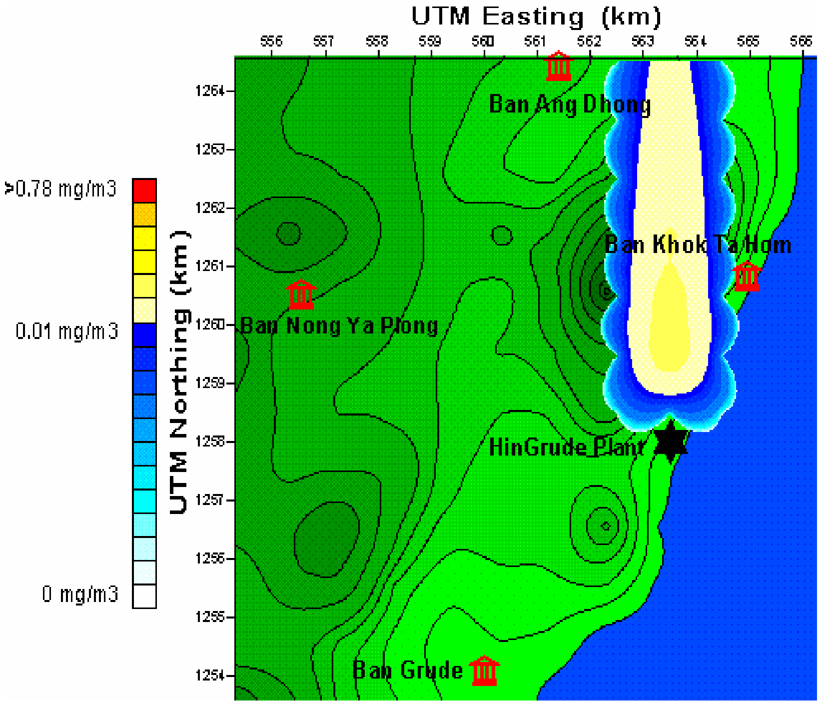
Appendix Figure J177 9th hour dispersion of SO_2 in summer



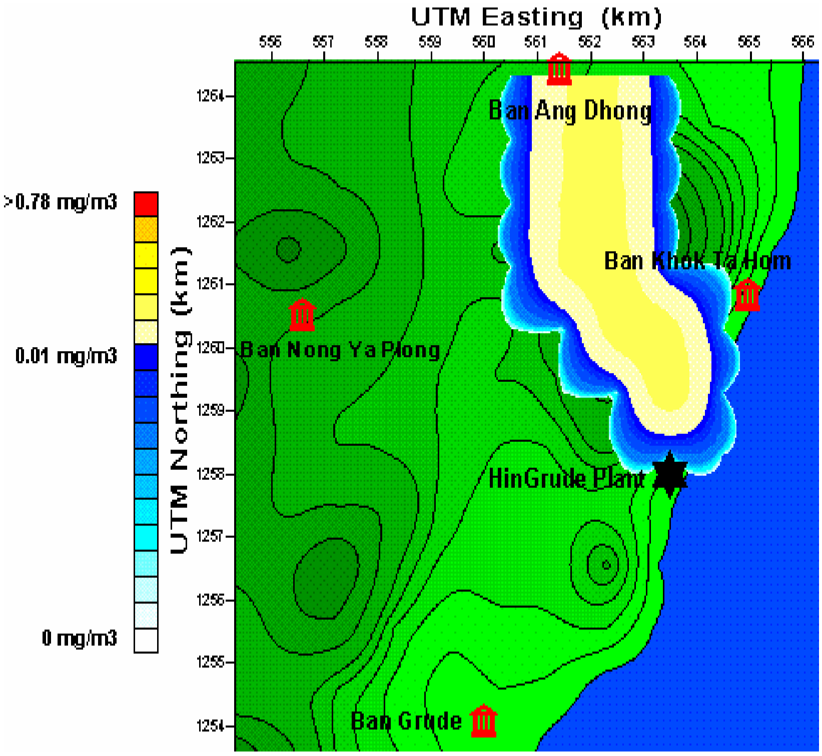
Appendix Figure J178 10th hour dispersion of SO_2 in summer



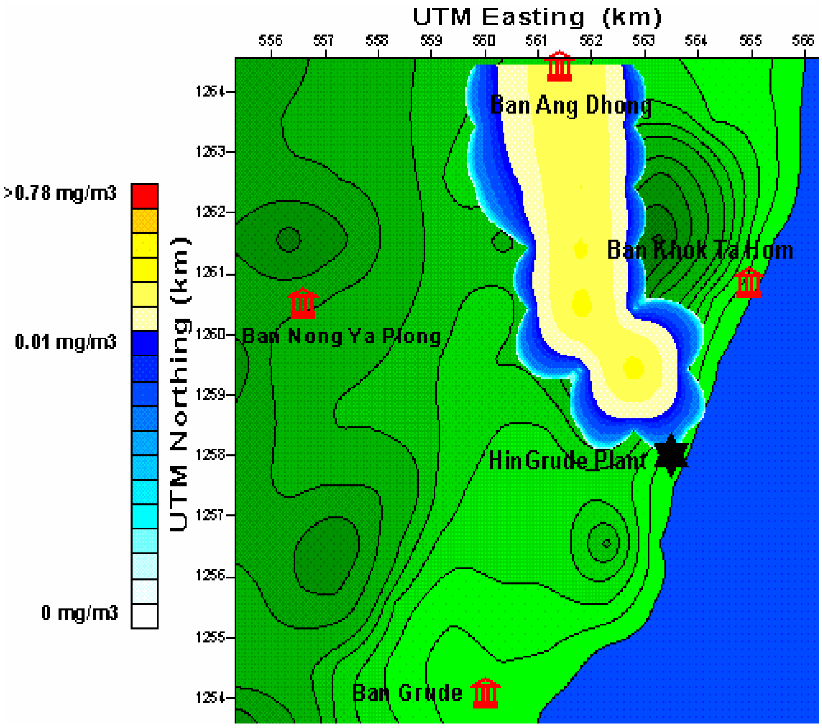
Appendix Figure J179 11th hour dispersion of SO_2 in summer



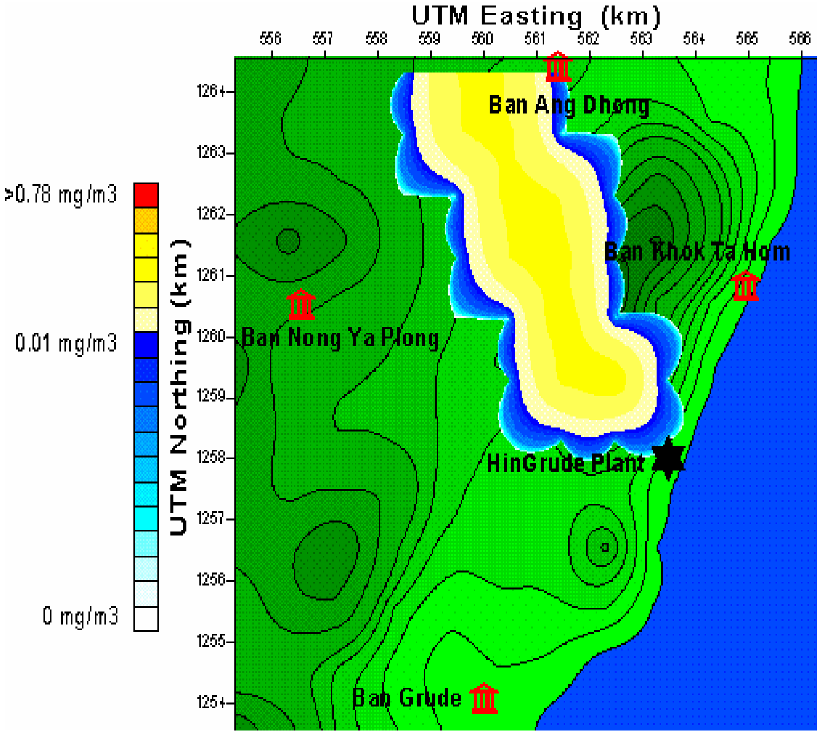
Appendix Figure J180 12th hour dispersion of SO_2 in summer



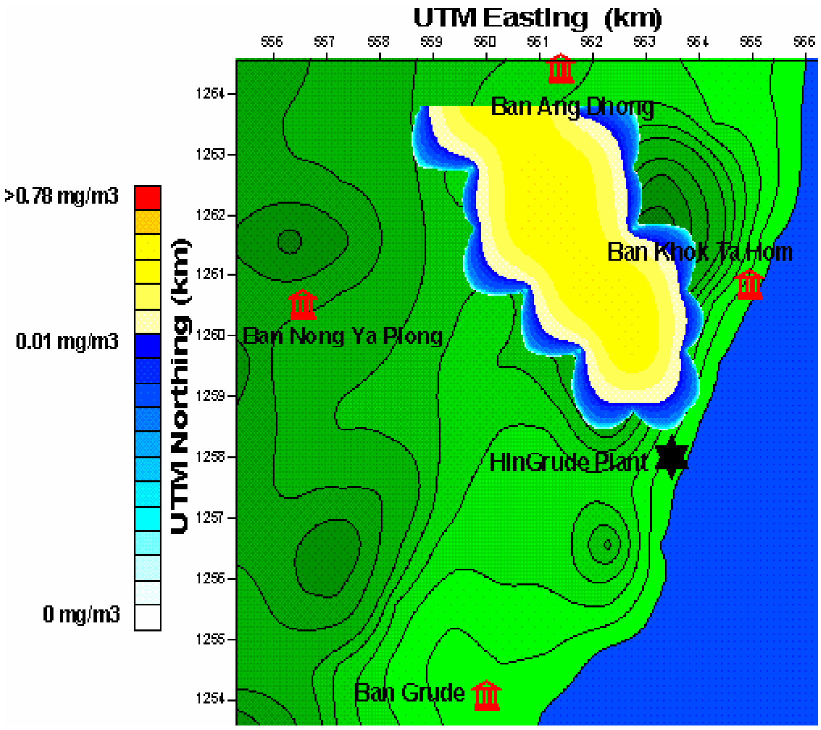
Appendix Figure J181 13th hour dispersion of SO_2 in summer



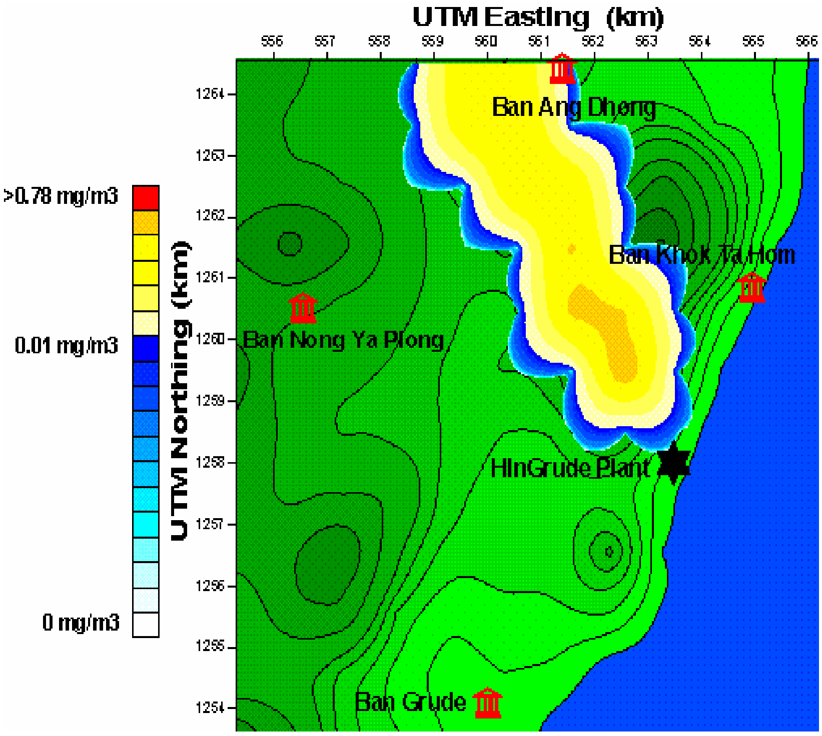
Appendix Figure J182 14th hour dispersion of SO_2 in summer



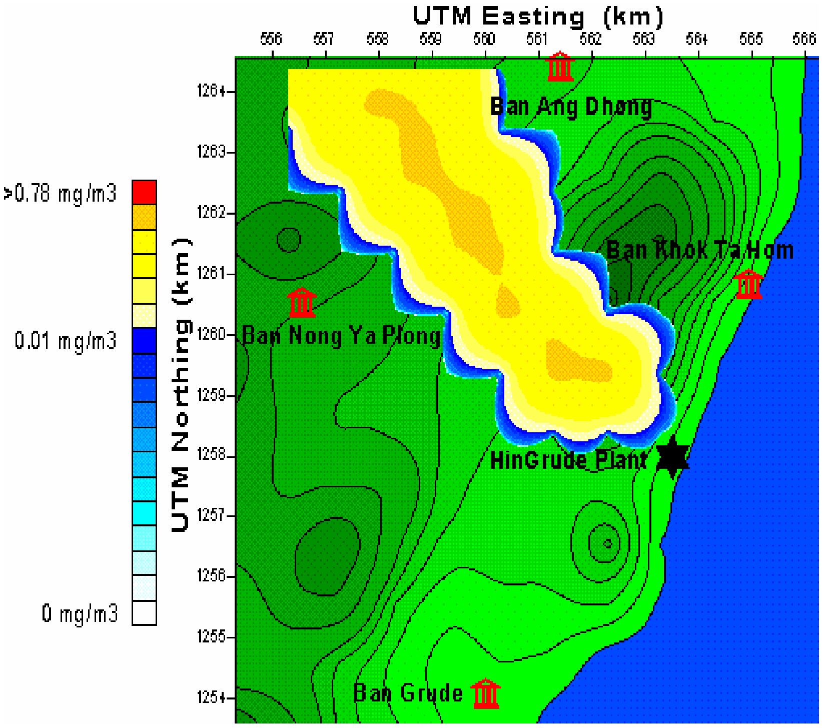
Appendix Figure J183 15th hour dispersion of SO_2 in summer



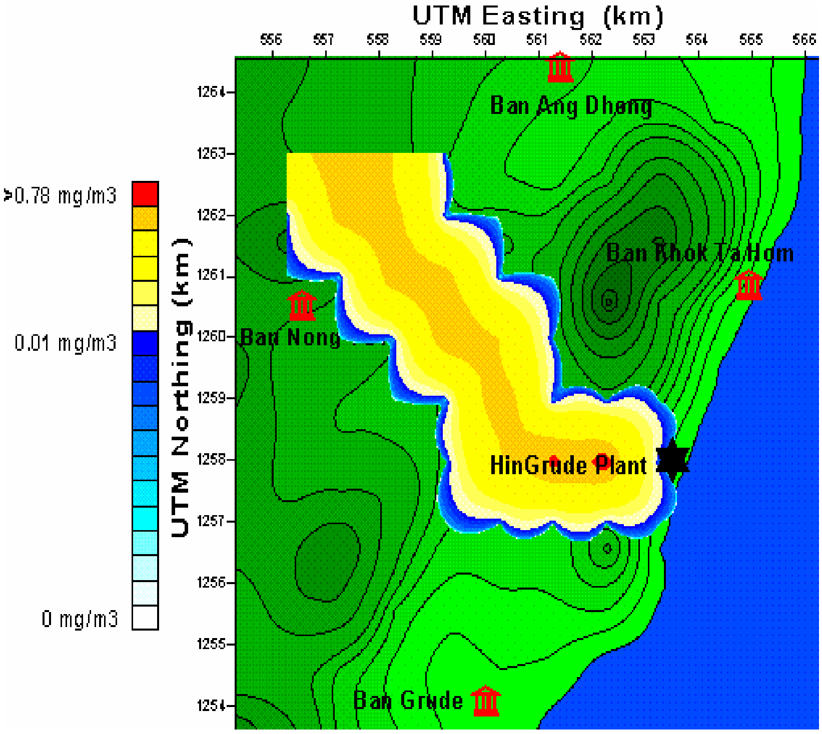
Appendix Figure J184 16th hour dispersion of SO_2 in summer



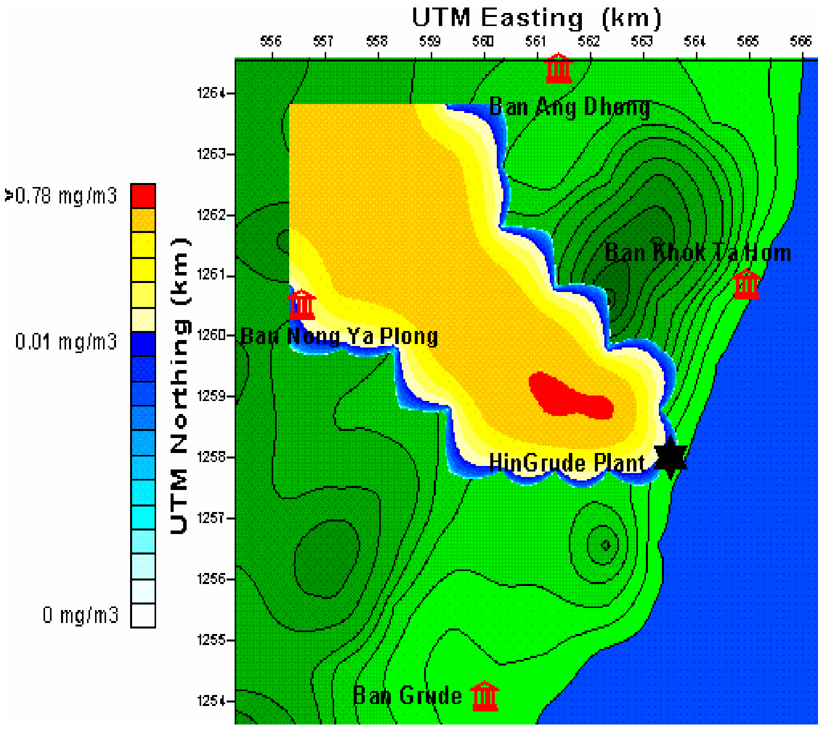
Appendix Figure J185 17th hour dispersion of SO_2 in summer



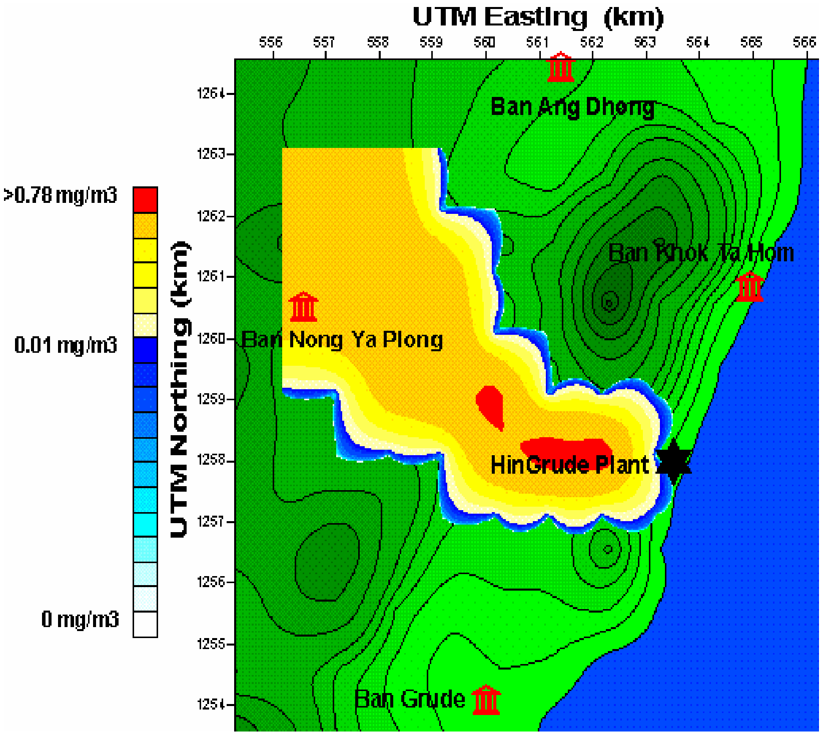
Appendix Figure J186 18th hour dispersion of SO_2 in summer



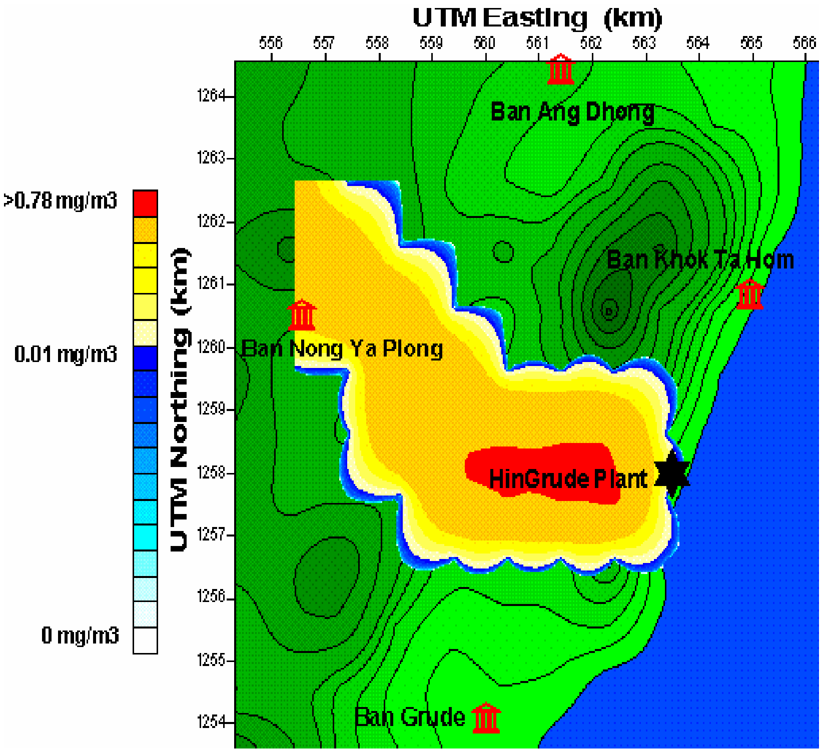
Appendix Figure J187 19th hour dispersion of SO_2 in summer



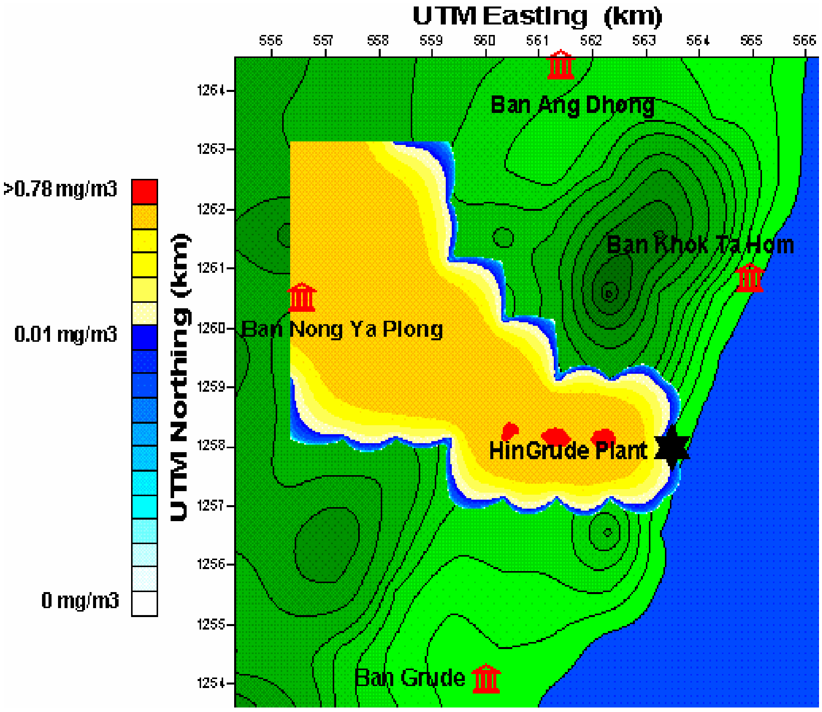
Appendix Figure J188 20th hour dispersion of SO_2 in summer



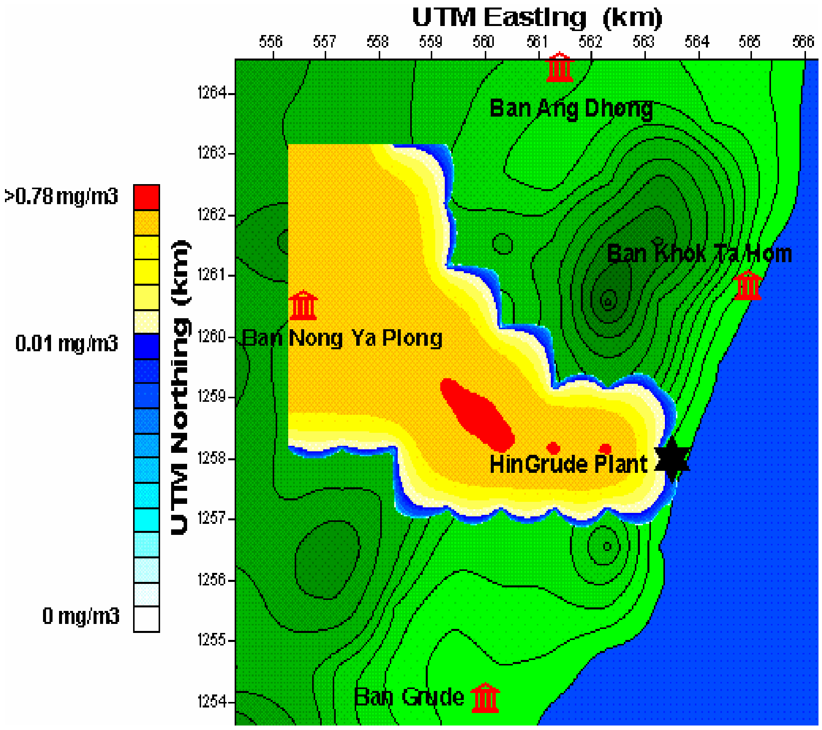
Appendix Figure J189 21st hour dispersion of SO_2 in summer



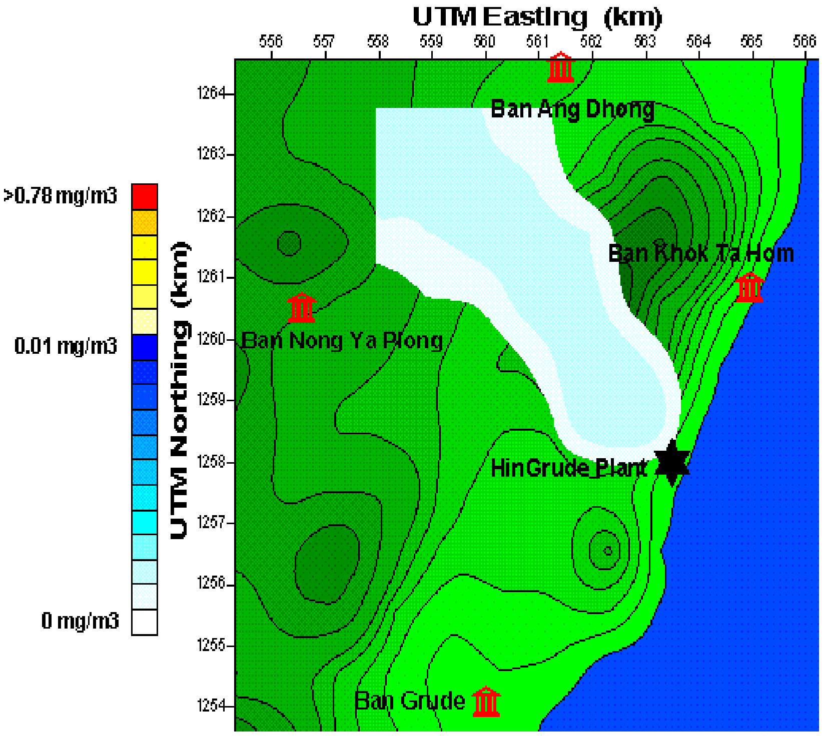
Appendix Figure J190 22nd hour dispersion of SO_2 in summer



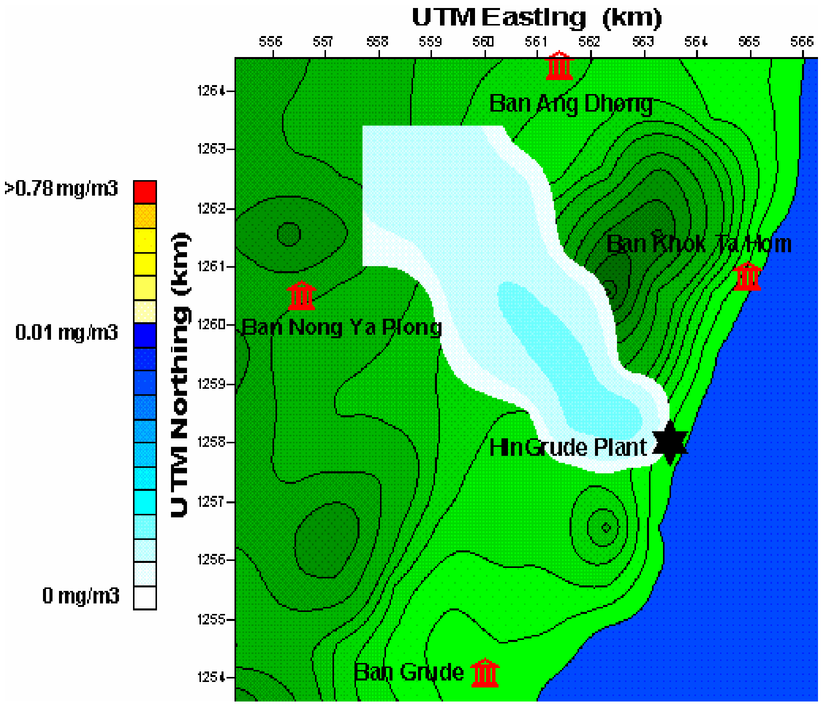
Appendix Figure J191 23rd hour dispersion of SO_2 in summer



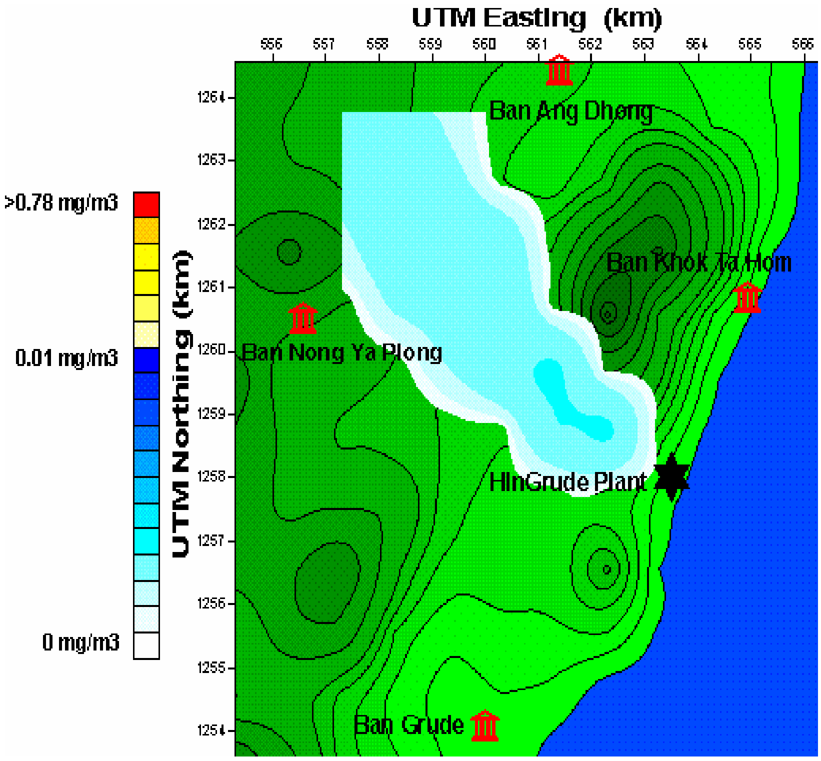
Appendix Figure J192 24th hour dispersion of SO_2 in summer



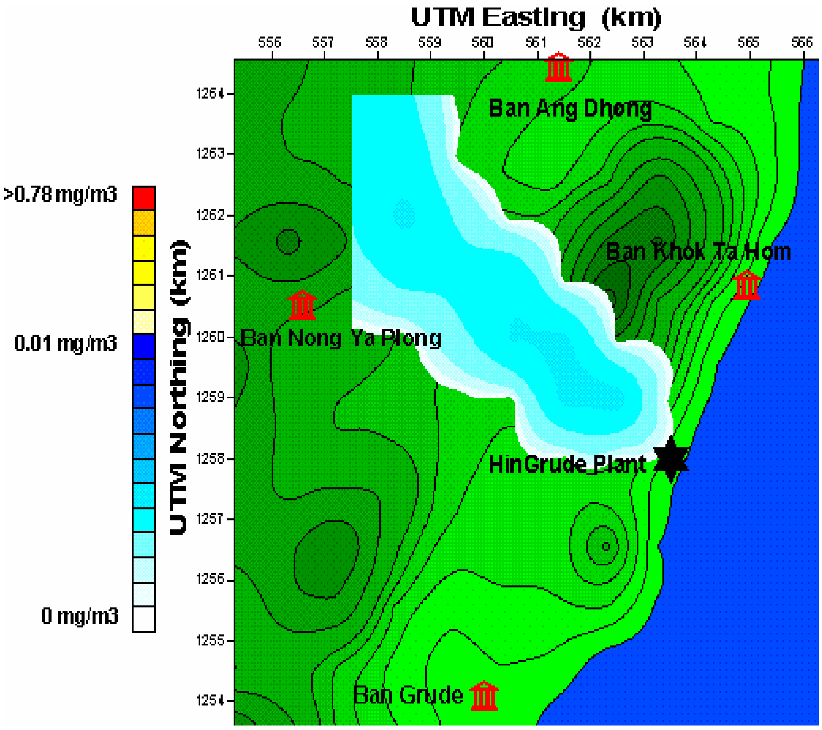
Appendix Figure J193 1st hour dispersion of SO_2 in rainy season



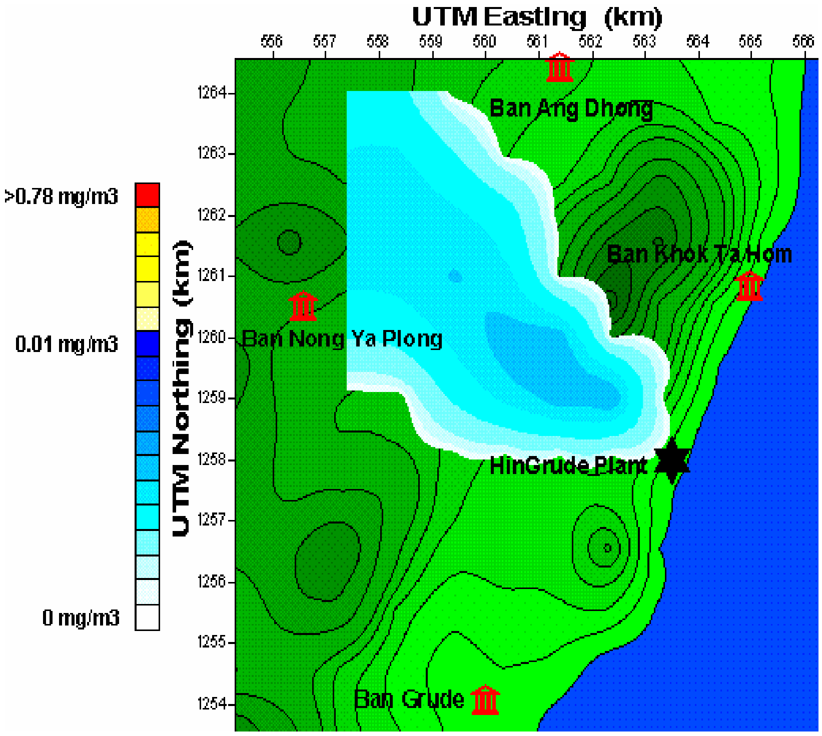
Appendix Figure J194 2nd hour dispersion of SO_2 in rainy season



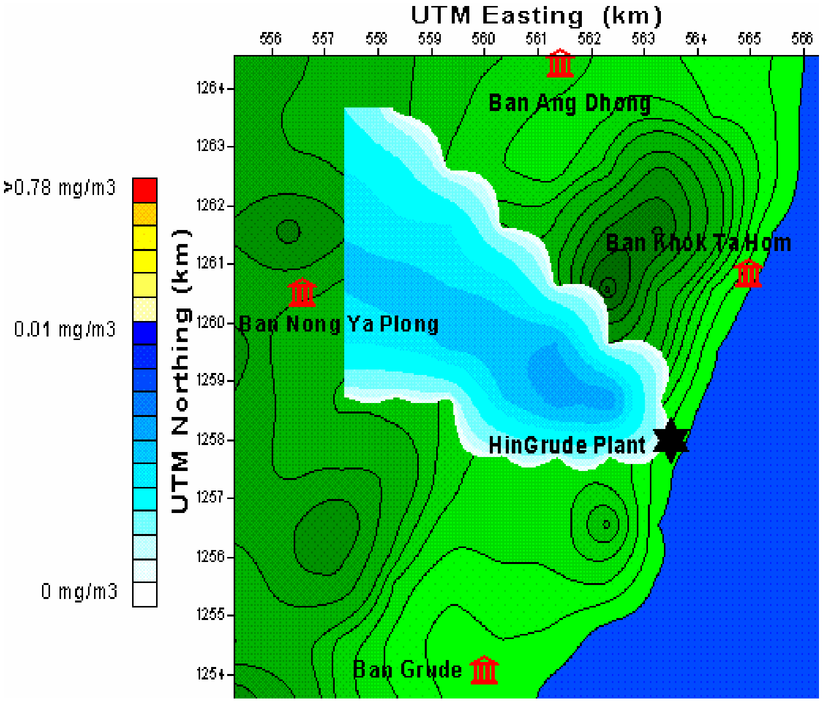
Appendix Figure J195 3rd hour dispersion of SO_2 in rainy season



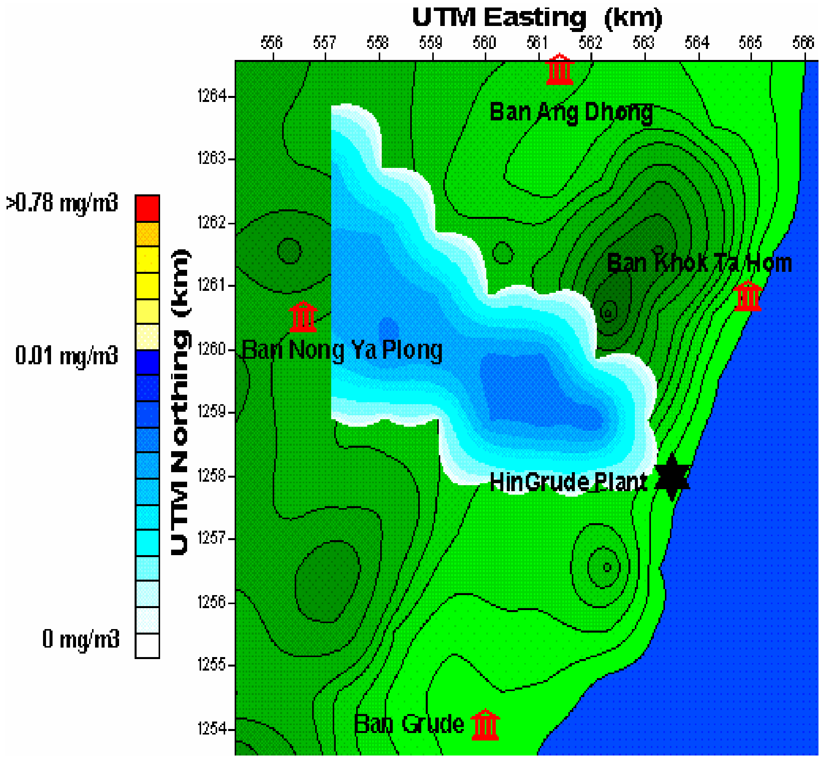
Appendix Figure J196 4th hour dispersion of SO_2 in rainy season



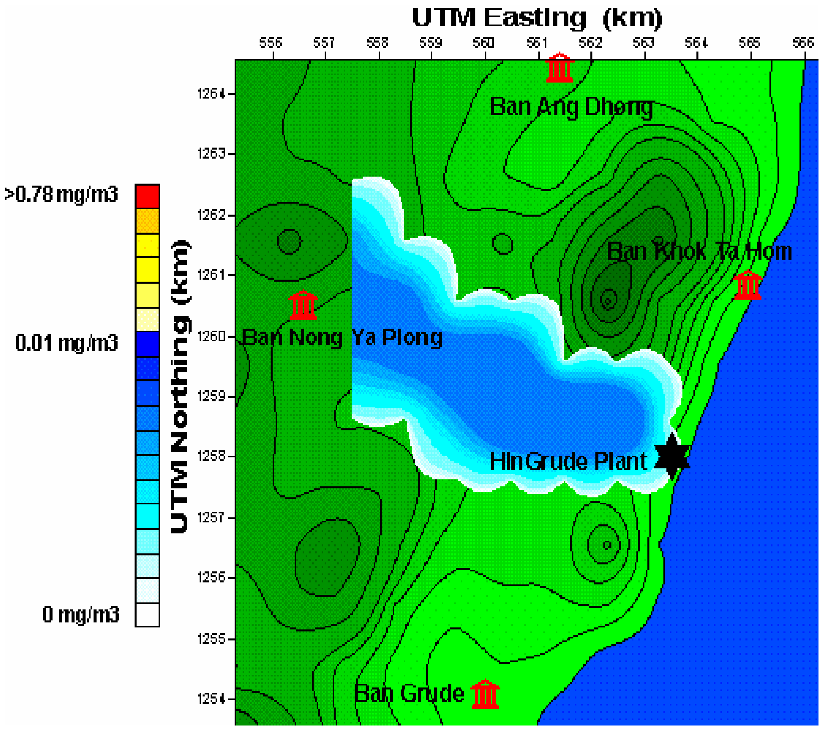
Appendix Figure J197 5th hour dispersion of SO_2 in rainy season



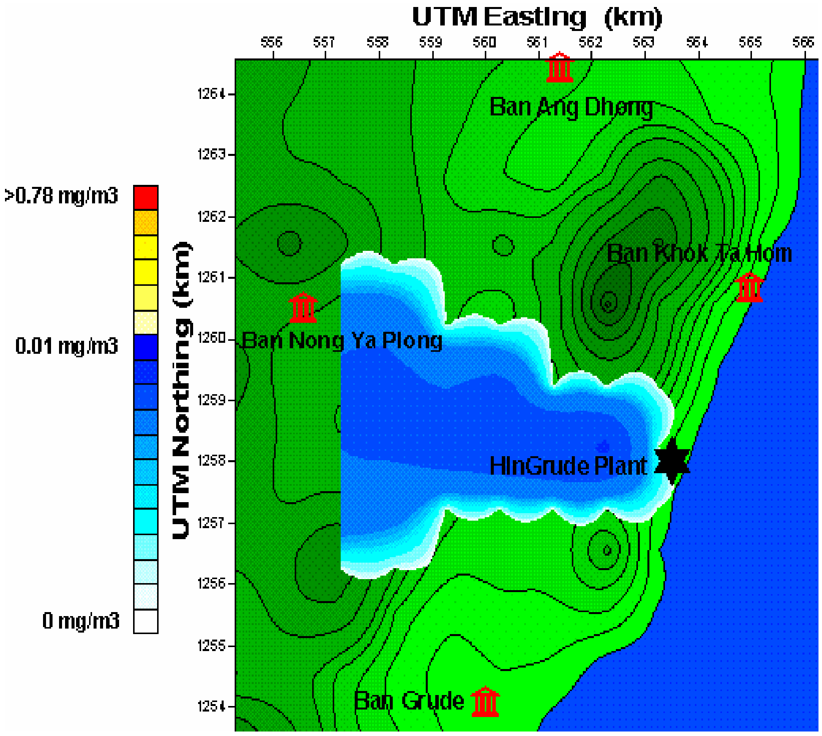
Appendix Figure J198 6th hour dispersion of SO_2 in rainy season



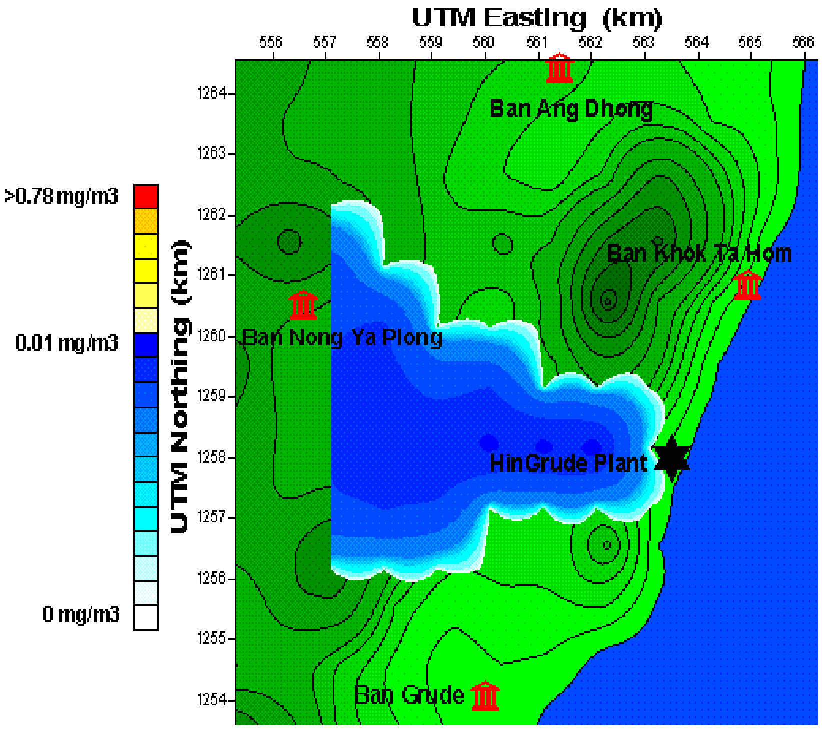
Appendix Figure J199 7th hour dispersion of SO_2 in rainy season



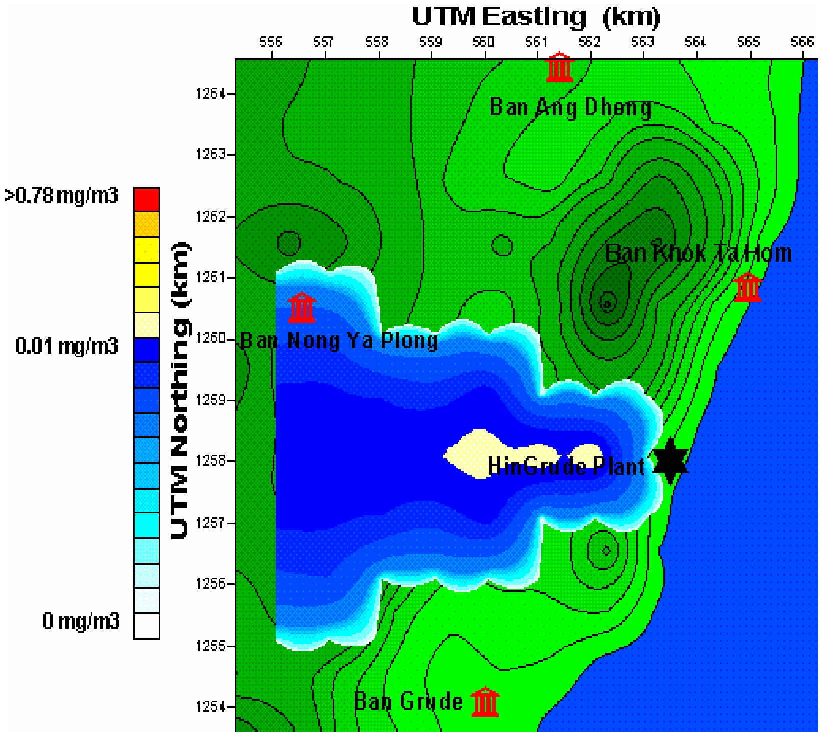
Appendix Figure J200 8th hour dispersion of SO_2 in rainy season



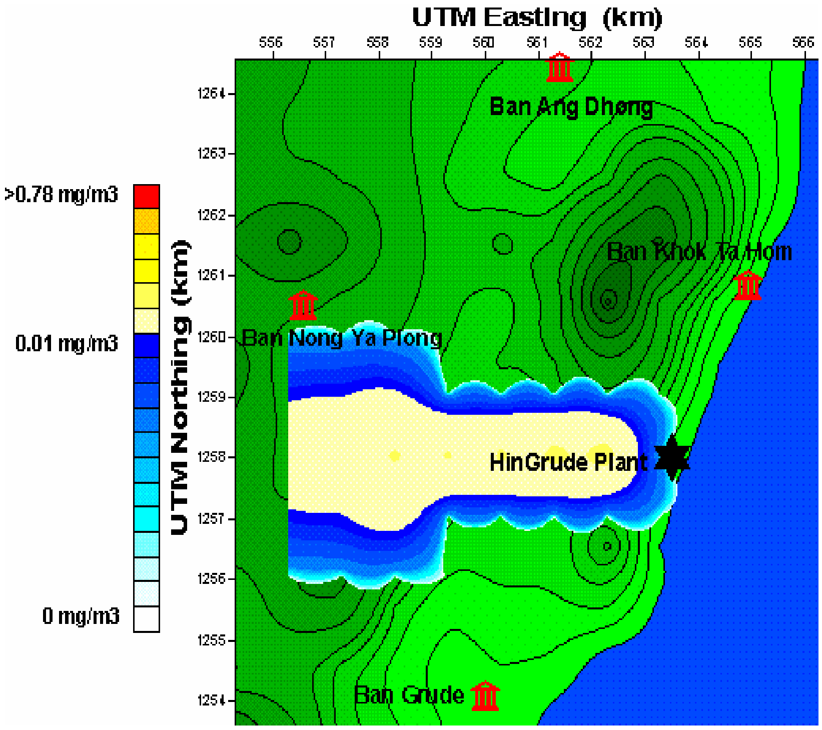
Appendix Figure J201 9th hour dispersion of SO_2 in rainy season



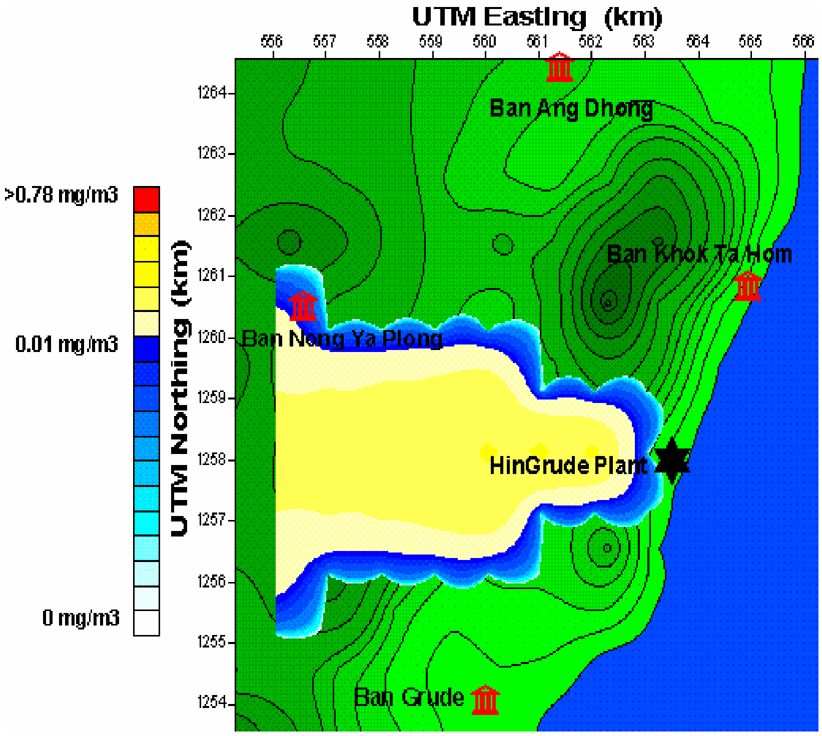
Appendix Figure J202 10th hour dispersion of SO_2 in rainy season



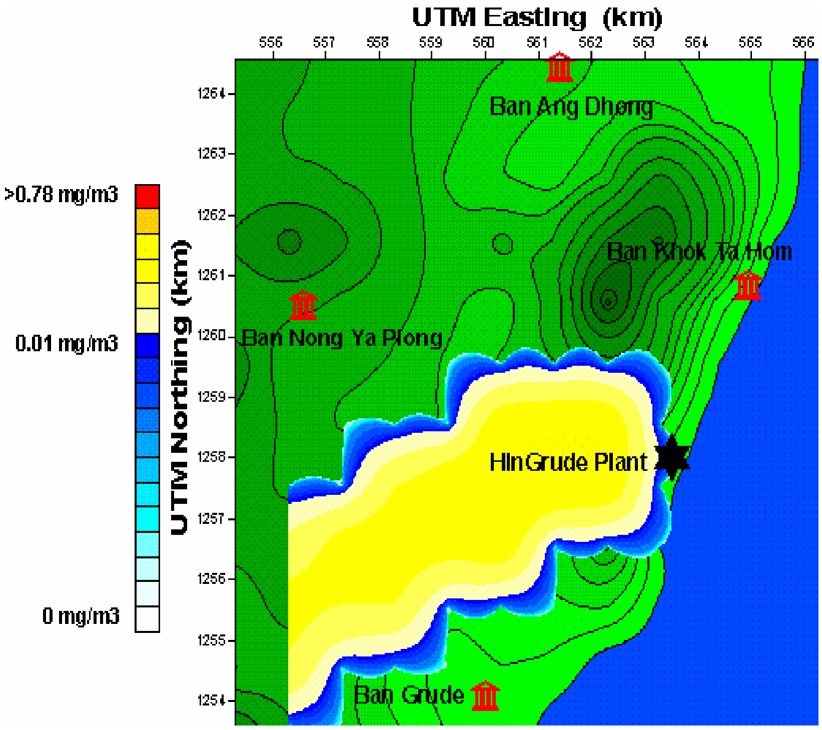
Appendix Figure J203 11th hour dispersion of SO_2 in rainy season



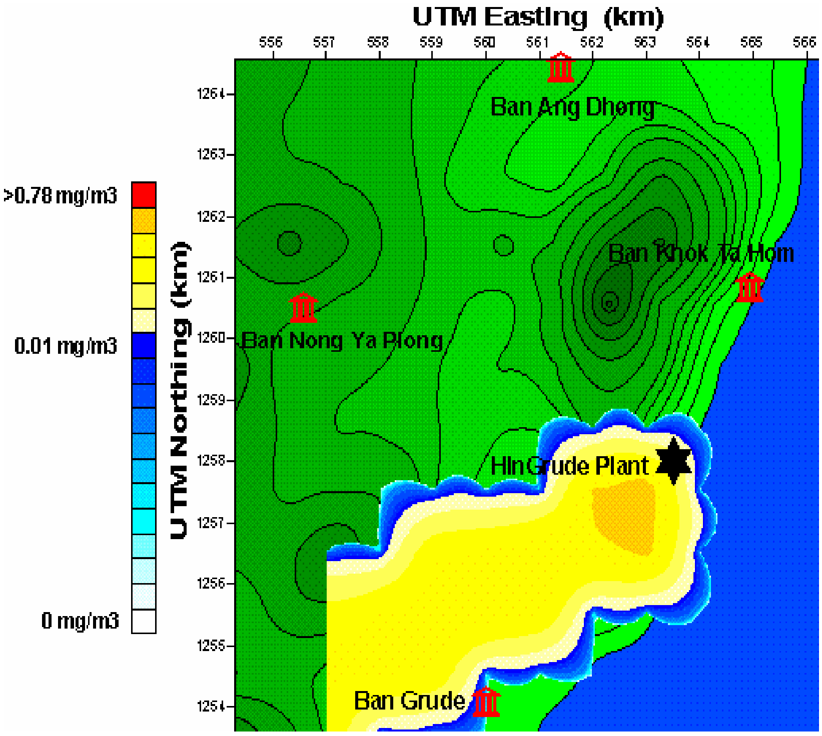
Appendix Figure J204 12th hour dispersion of SO_2 in rainy season



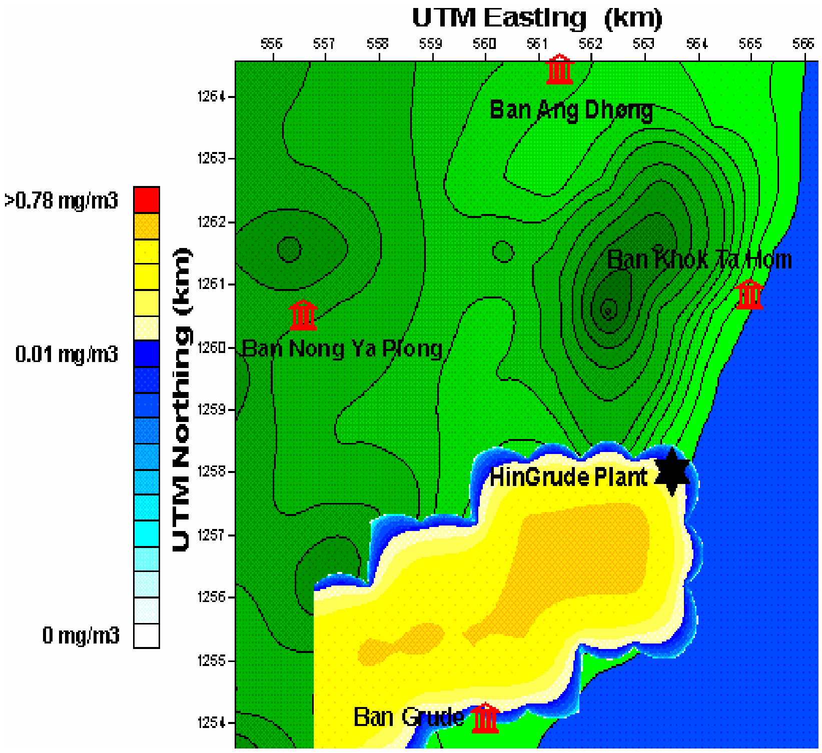
Appendix Figure J205 13th hour dispersion of SO_2 in rainy season



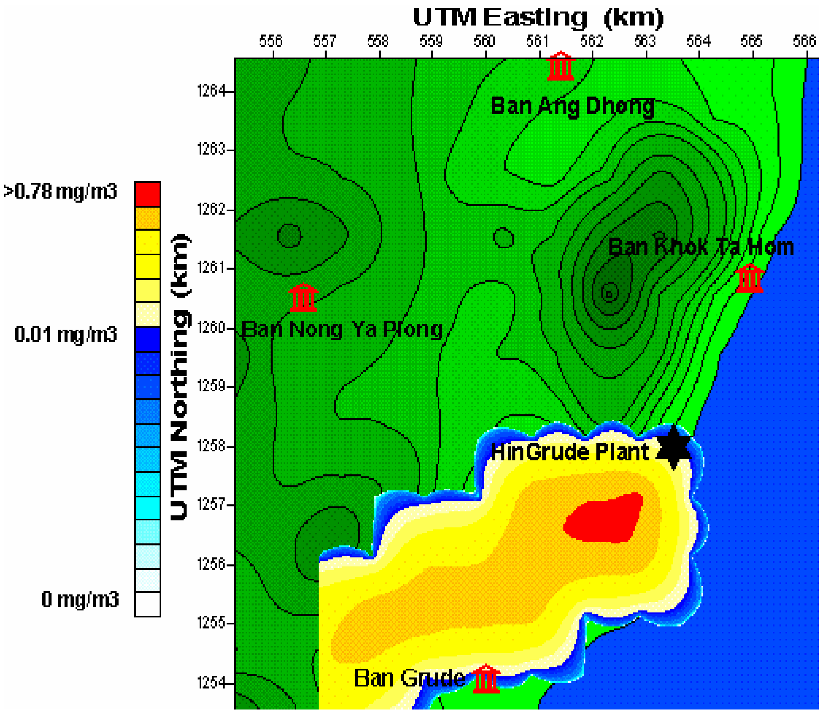
Appendix Figure J206 14th hour dispersion of SO_2 in rainy season



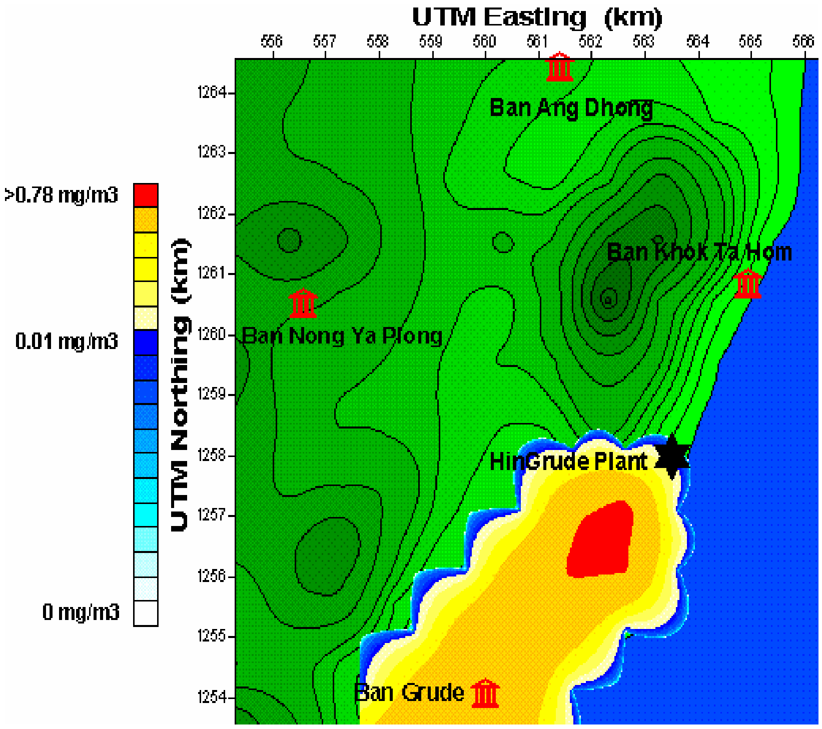
Appendix Figure J207 15th hour dispersion of SO_2 in rainy season



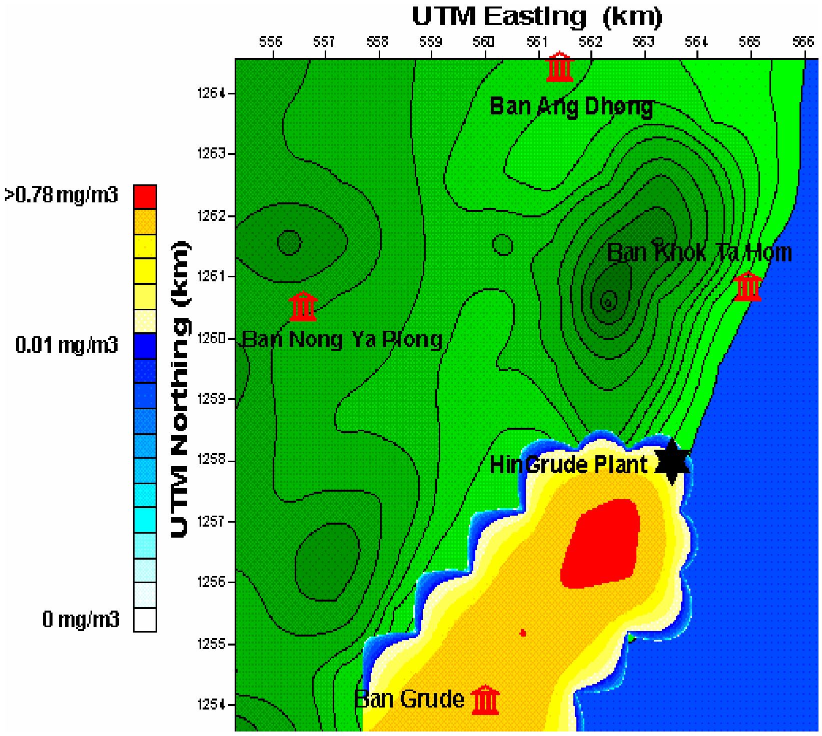
Appendix Figure J208 16th hour dispersion of SO_2 in rainy season



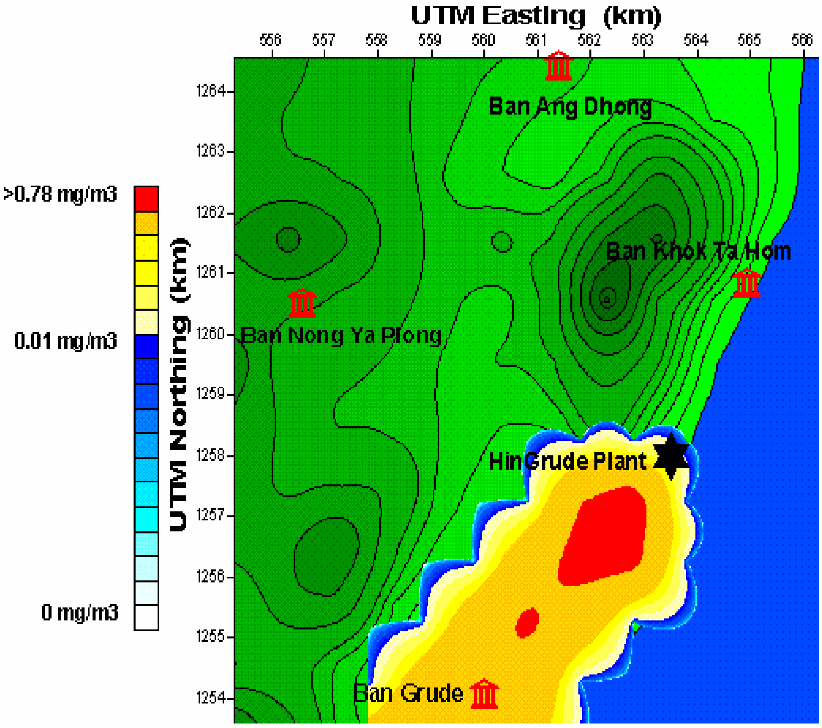
Appendix Figure J209 17th hour dispersion of SO_2 in rainy season



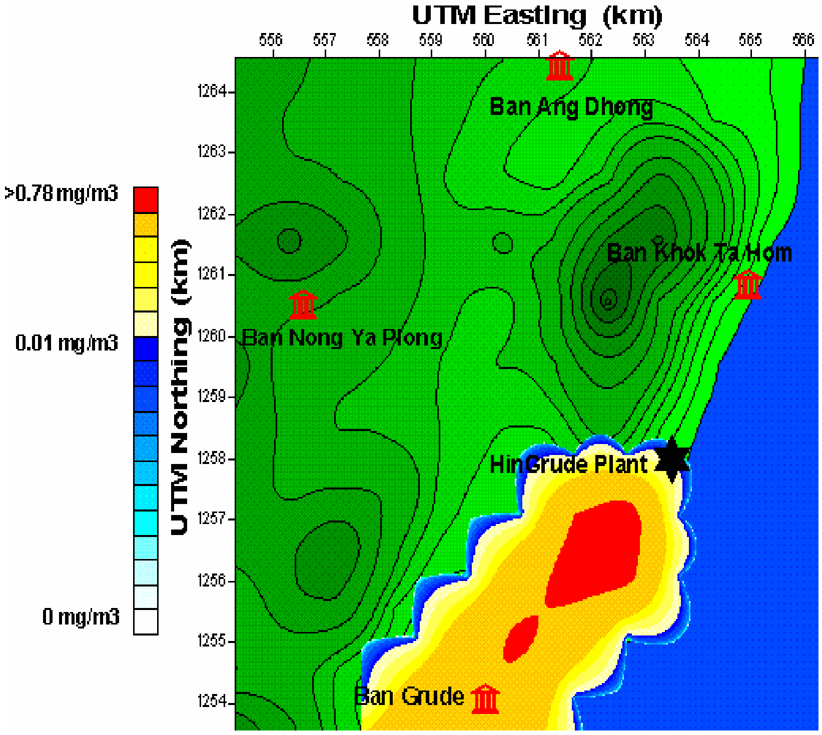
Appendix Figure J210 18th hour dispersion of SO_2 in rainy season



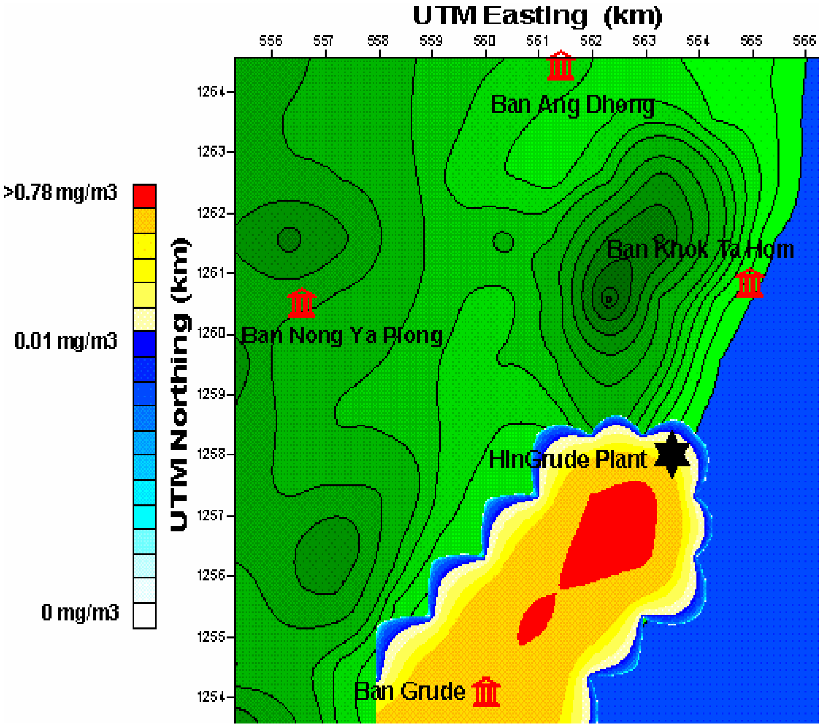
Appendix Figure J211 19th hour dispersion of SO_2 in rainy season



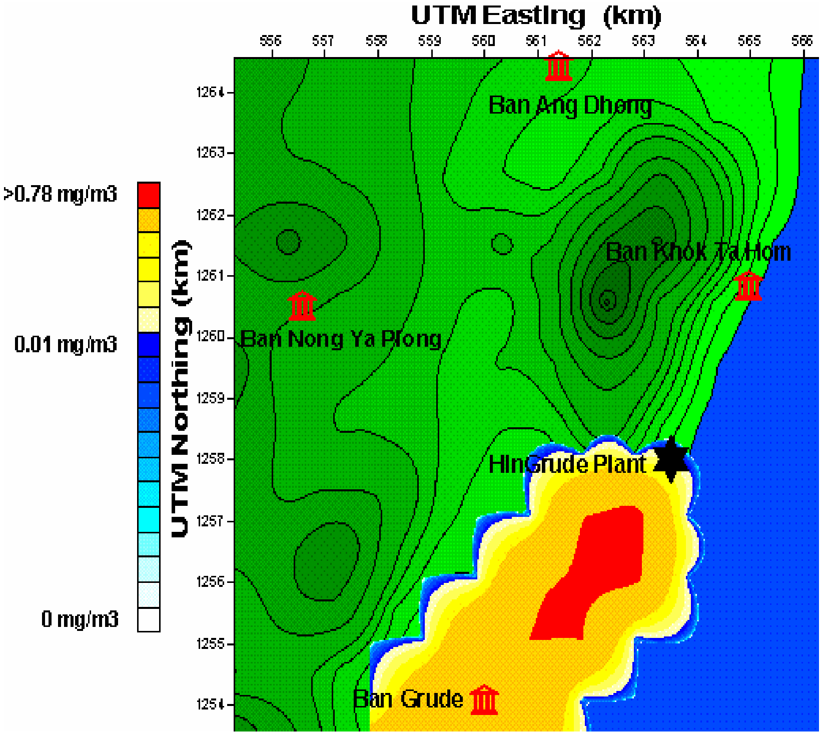
Appendix Figure J212 20th hour dispersion of SO_2 in rainy season



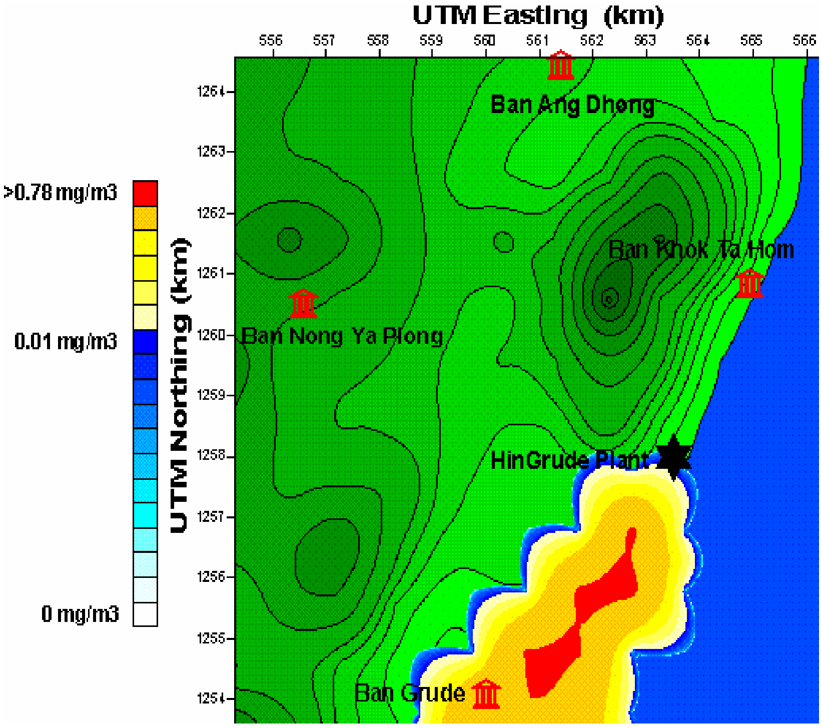
Appendix Figure J213 21st hour dispersion of SO_2 in rainy season



Appendix Figure J214 22nd hour dispersion of SO_2 in rainy season



Appendix Figure J215 23rd hour dispersion of SO_2 in rainy season



Appendix Figure J216 24th hour dispersion of SO_2 in rainy season