Cost-Benefit Optimization Approach to Air Pollution Management

Dr. Paolo Zannetti, QEP
The EnviroComp Institute and EnviroComp Consulting, Inc.
www.envirocomp.org www.envirocomp.com

UPWIND-DOWNWIND CONFERENCE 2014: Built Environment – Foundation for Cleaner Air Sheraton Hotel, HAMILTON, Ontario, CANADA
24 February 2014

An Introduction to Our Activities

- 40+ years of Research and Development in air pollution and computer modeling
  - pure research in the fields of atmospheric diffusion and numerical computation
  - publications, seminars, and courses
  - project management
  - environmental consulting
  - editorial productions
  - expert testimony
- Two "hats":
  - R&D activities: The EnviroComp Institute (www.envirocomp.org)
  - Consulting: EnviroComp Consulting, Inc. (www.envirocomp.com)

The EnviroComp Institute

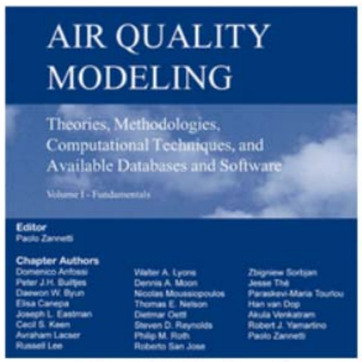
- Non-profit
- Publications, seminars, and courses
- Main activity: production of electronic books on CD-ROM:
  - Air Pollution Modeling
    - http://envirocomp.org/books/aqm.html
  - Groundwater modeling
    - http://envirocomp.org/books/gwm.html
  - Air Pollution in the Middle East
    - http://envirocomp.org/books/aap.html
  - Engineering Uplift of Venice
    - http://envirocomp.org/books/venice.html

AQM – Four Volumes

Air Quality Modeling Book Series

These books take an in-depth look at the fundamentals of air pollution modeling: from a review of air pollution meteorology, to an introduction to Gaussian plume models; from a discussion of plume rise formulations, to a review of Eulerian grid models. With individual chapters written by experts in their fields, these books give environmental professionals a solid foundation for understanding modeling techniques using both semi-empirical formulations and well-established atmospheric science.

Air Quality Modeling I



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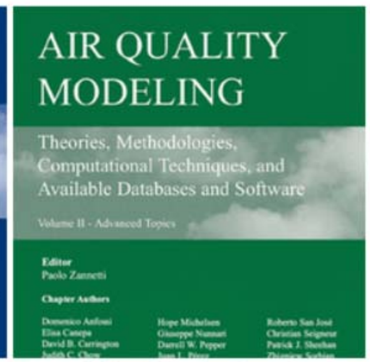
Air Quality Modeling II



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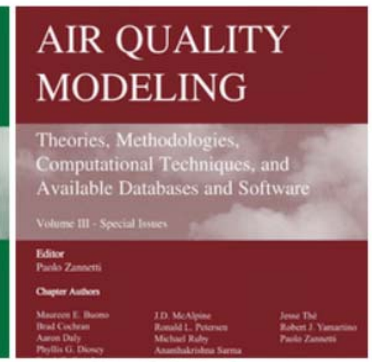
Air Quality Modeling III



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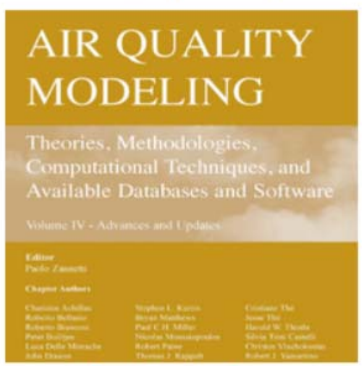
Air Quality Modeling IV



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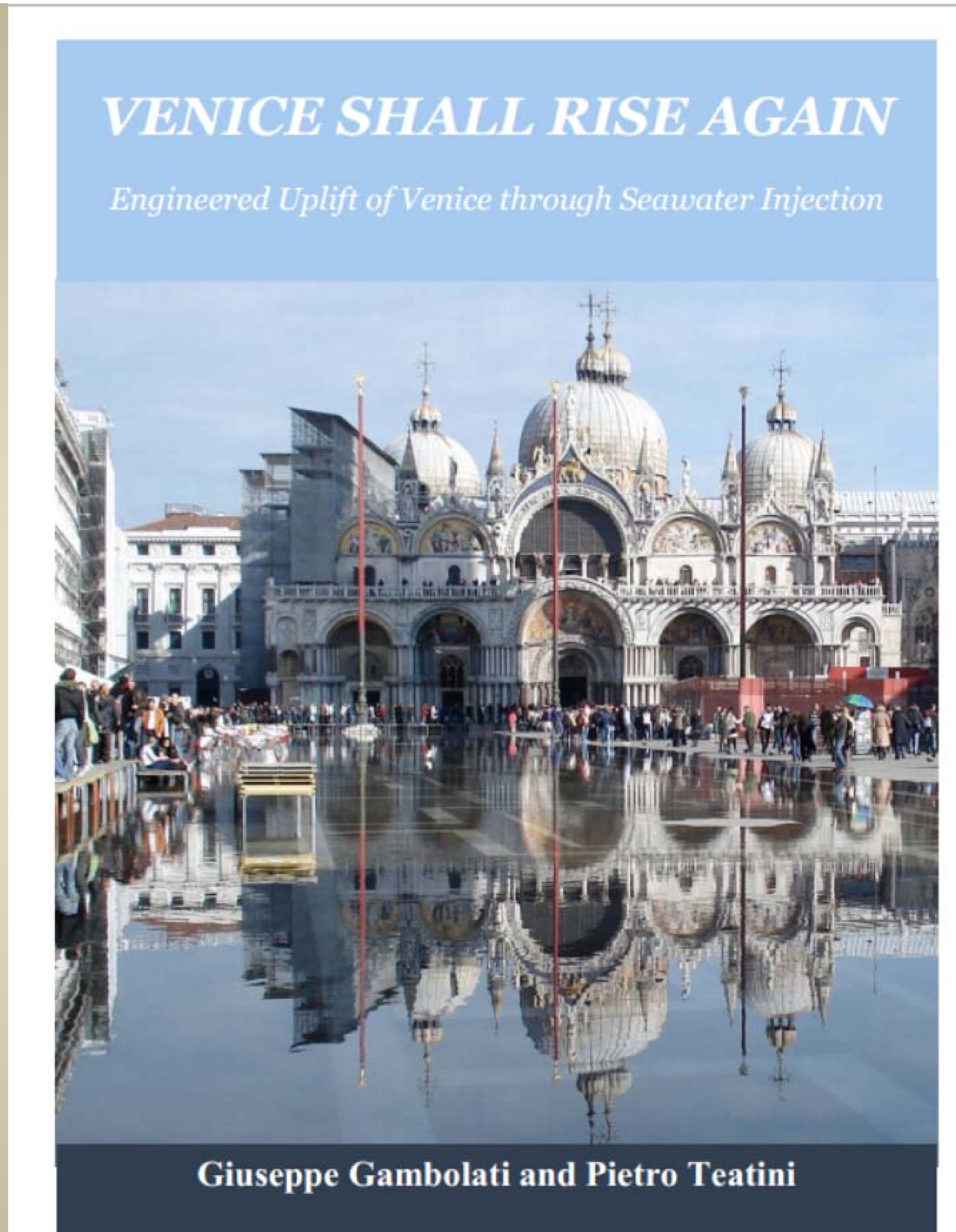

VENICE SHALL RISE AGAIN
Engineered Uplift of Venice through Seawater Injection
Giuseppe Gambolati and Pietro Teatini

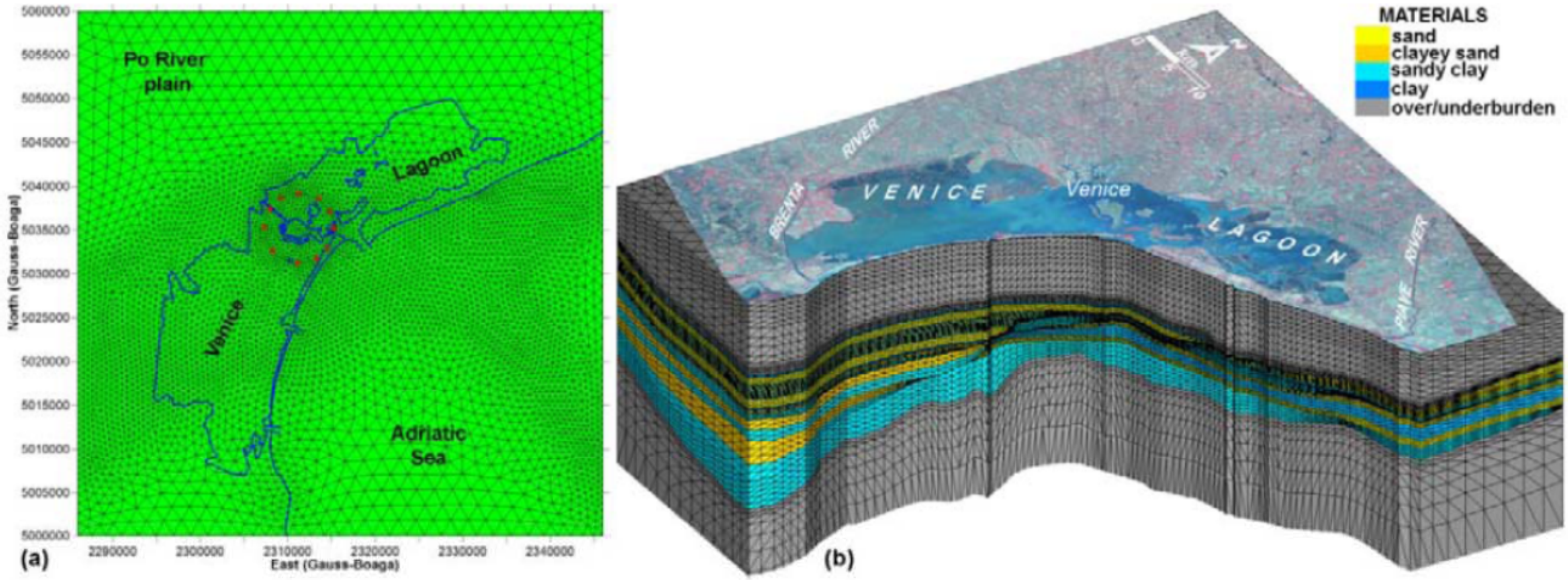


Figure 38. (a) Plan view of the three-dimensional finite element grid. The location of the injection wells is shown. (b) Axonometric view of the three-dimensional FE grid sectioned along the coastline. The colors are representative of the various lithotypes detected within the PLS-3, PLS-2 and PLC-2 formations and the overlying and underlying units. The vertical exaggeration is 5.

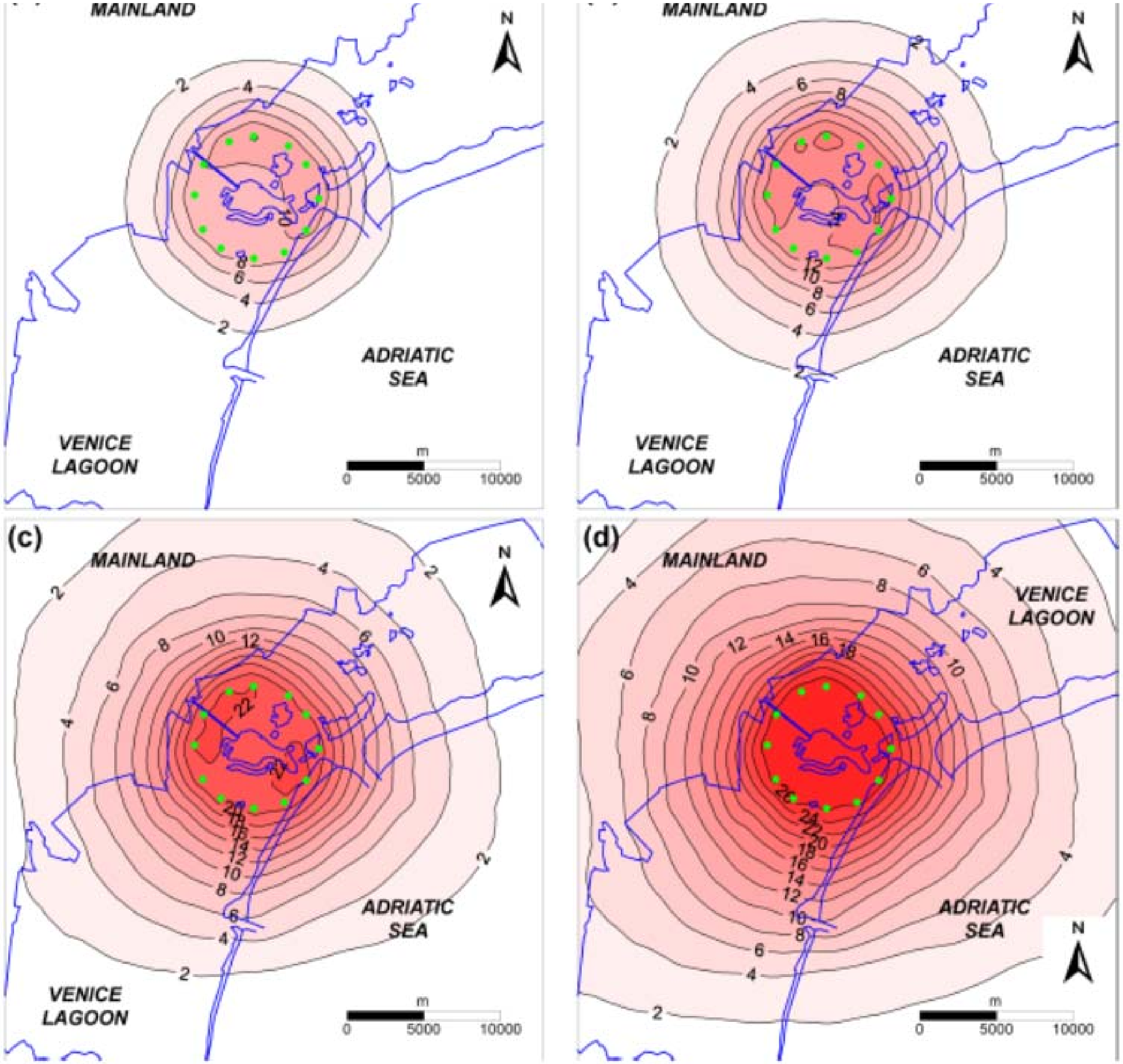


Figure 41. Predicted uplift (cm) after (a) 1, (b) 2, (c) 5, and (d) 10 years of injection. The injection wells marked in green (modified after Teatini et al., 2011b). (video5)

EnviroComp Consulting, Inc.

- Main activity: Litigation consulting
  - Accidental releases, e.g.:
    - Chlorine
    - Ammonia
    - Black smoke
    - Pesticides
    - Odors
  - Chronic exposure (e.g., hexavalent chromium, metals, dioxins, formaldehyde, benzene)
    - Indoor working environment
    - Neighboring industrial activities
- See: "Selected Projects" at www.envirocomp.com

Today's Topic:

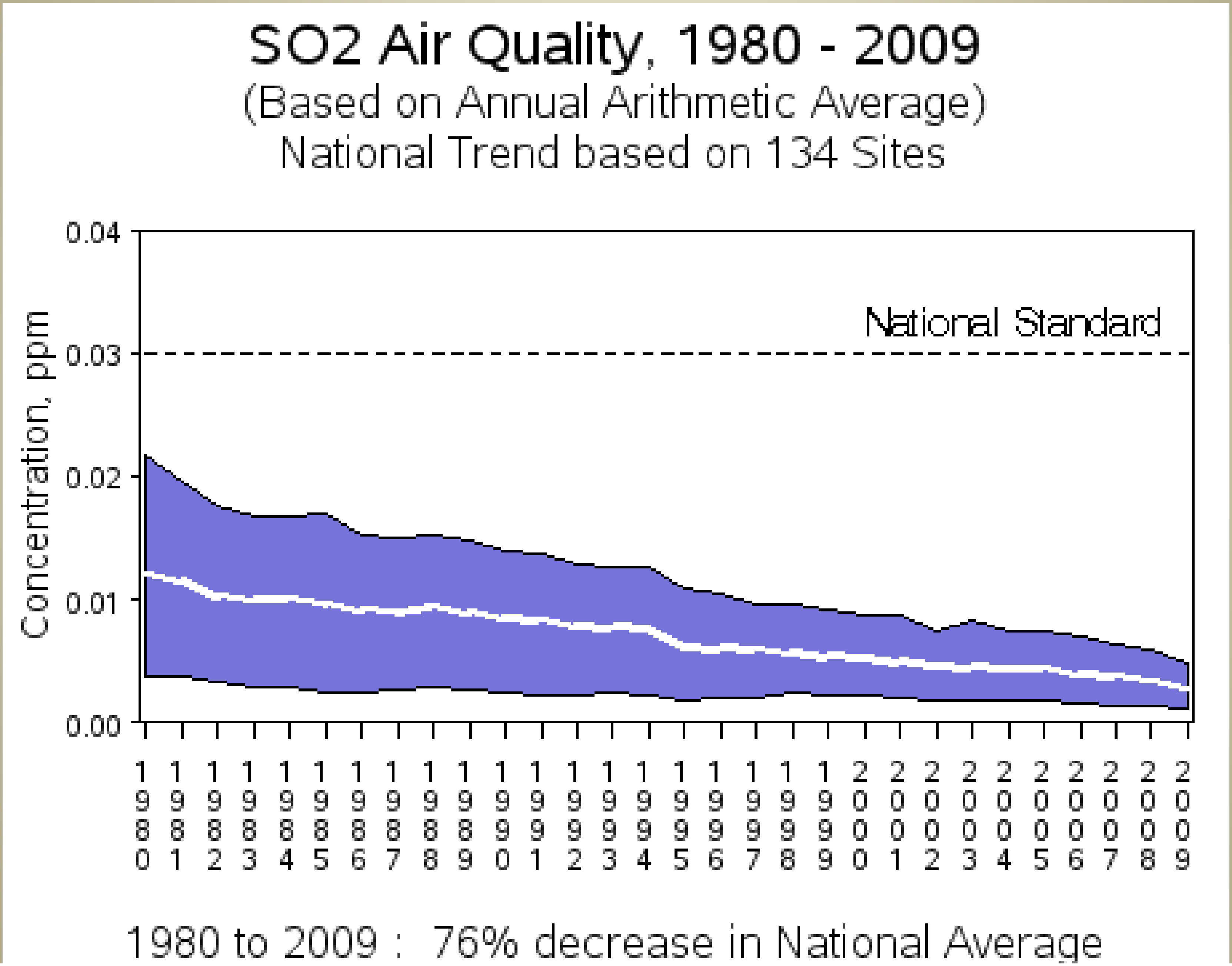
Cost-benefit Optimization Approach to Air Pollution Management

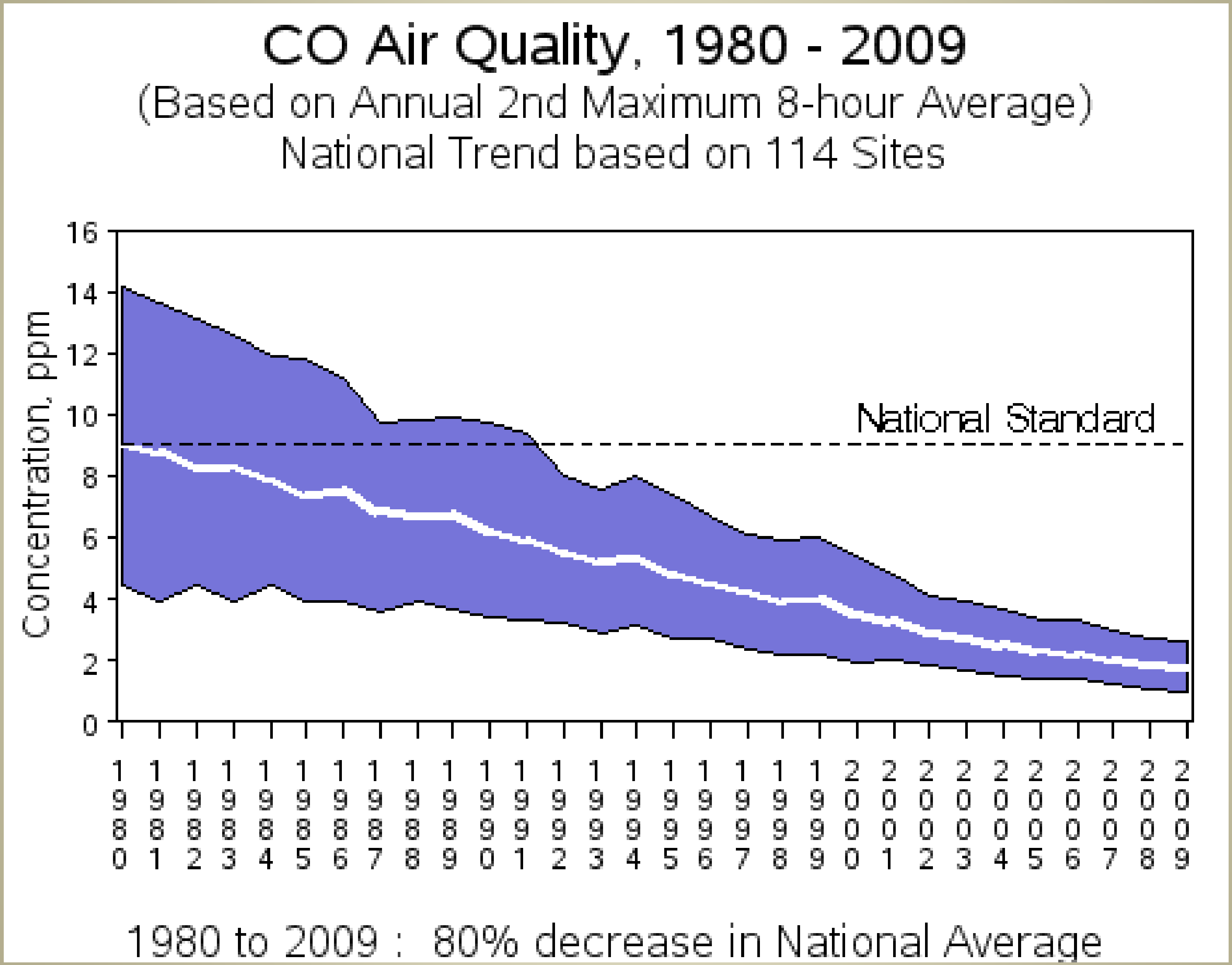
History of Air Quality Objectives

Two main goals:

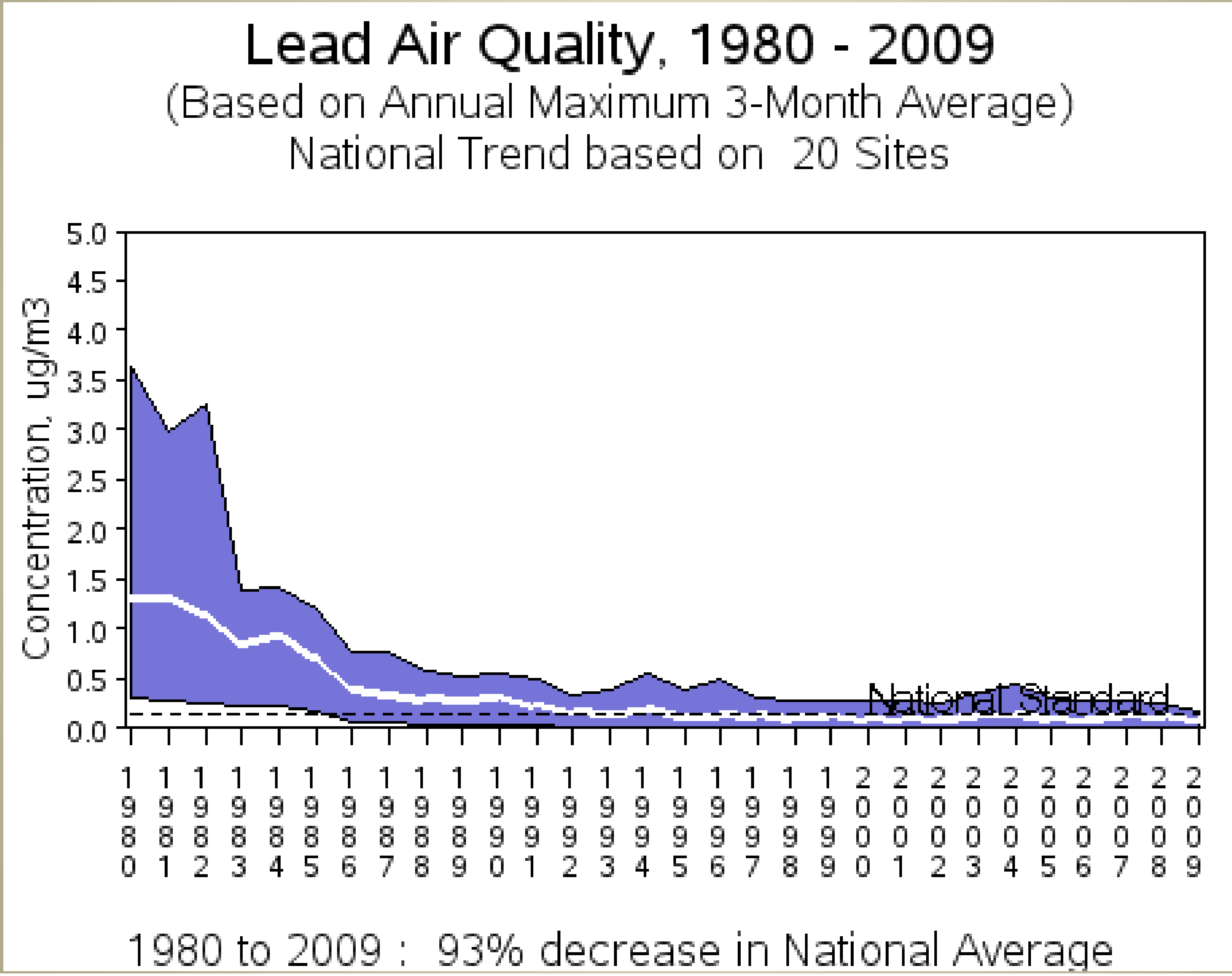
1. The improvement of air quality in areas contaminated by air pollution (e.g., US Clean Air Act of 1970) ➔ AQ standards
2. The protection of regions with good air quality from possible future deterioration due to urban and industrial development (e.g., US Prevention of Significant Deterioration, 1977) ➔ better than AQ standards

Major Results!




CO Air Quality, 1980 - 2009
(Based on Annual 2nd Maximum 8-hour Average)
National Trend based on 114 Sites
Concentration, ppm
16
14
12
10
8
6
4
2
0
National Standard
1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009
1980 to 2009 : 80% decrease in National Average

(1978 standard = 1.5 μg/m³ - 2008 standard = 0.15 μg/m³)



Costs vs. Benefits

- Enormous costs of study, design, implementation, and enforcement of regulations, plus the costs carried by businesses and industries for compliance
- Questions:
  - Were benefits greater than costs?
  - Were air quality improvement plans designed to maximize benefits or minimize costs?
  - Could we have applied better cost-benefit planning and achieved better results?
  - Can we use cost-benefit optimization in the future?
    (we should focus on what can be done today with the current technology!)

It is a Fact! Let's Admit it!

- Advanced computer simulation/optimization techniques have never been used so far to guide the actions of governments and agencies toward a well organized
  - maximization of benefits (with fixed costs) or
  - minimization of costs (with fixed benefits)
- The actions of governments have focused instead on
  1. air quality standards (that should not be exceeded, but often are) verified by air quality measurements, even though air monitoring is costly and we cannot of course measure all pollutants in all locations;
  2. emission standards, that again are not always easy to control;
  3. enforcement, often partial and selective.

Some Data

- Benefits: According to a 1997 EPA Report to Congress (http://www.epa.gov/oar/caa/40th_highlights.html), the first 20 years of Clean Air Act programs, from 1970 - 1990, led to the prevention in the year 1990 of:
  - 205,000 premature deaths,
  - 672,000 cases of chronic bronchitis,
  - 21,000 cases of heart disease,
  - 843,000 asthma attacks,
  - 189,000 cardiovascular hospitalizations,
  - 10.4 million lost I.Q. points in children - from lead reductions, and
  - 18 million child respiratory illnesses
- Costs: it has been estimated that the costs of the 1990 Clean Air Act Amendments over the period 1990-2020 in the US were 380 billion dollar (in 2006 US$)
  (http://www.epa.gov/oar/sect812/feb11/fullreport_rev_a.pdf)

It is Reasonable to Believe...

- … that today's computer simulation/optimization techniques offer a tool for optimal planning that should play a key role in the future
- This is particularly true for emerging countries, e.g., China
  - rapid industrialization,
  - distressing deterioration of air quality, especially in major cities

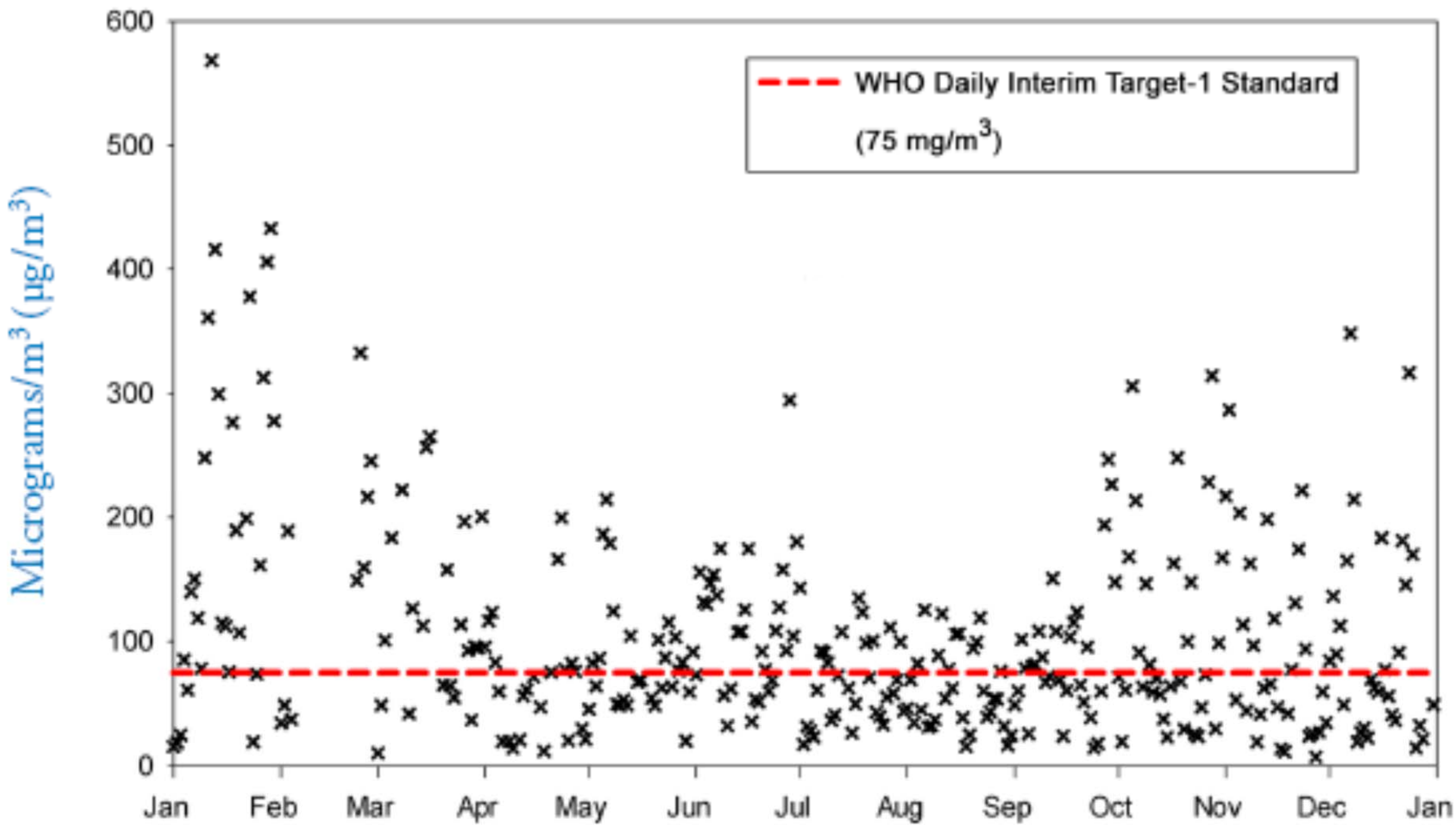
What do we Recommend to Emerging Countries?

- We all expect countries like China eventually to follow the historical pattern of the West (e.g., Europe and North America),
  - after major industrial developments ➔development of environmental protection regulations
  - major investments in remediation and emission control
  - positive results that can be measured and verified in most (but certainly not all) regions.
- But is this historical path the best, today, especially for emerging countries that need fast solutions at minimum costs?
- We believe that any country today investing funds for air quality improvement/protection can benefit from planning through computer simulation modeling and optimization techniques
- The discussion below elaborates our views on this matter and presents the design of a conceptual software prototype developed for this purpose

China, as an Example

- Special place for its size and the rapidity of its recent industrial and urban growth
- High levels of urban and industrial air pollution in many areas of its territory, especially in its highly populated coastal region
- History teaches us that, eventually, with time, increase in wealth, pressure from public opinion, industrial awareness, and proper government actions and investments, these problems will be mitigated
- The issue is how to accelerate this process and, more importantly, how to make sure that investments will produce maximum benefits

2013 Daily $PM_{2.5}$ Concentrations Measured in Beijing, China



China: Unique Historic Position

- Take full advantage of previous experiences in the Western world, including successes and mistakes, good investments and wasteful ones
- Intelligent use of today's advanced computer simulation tools - Air Quality Models - that have been well tested and calibrated
- These tools, combined with other computer methods (e.g., optimization simulations and cost-benefit analysis), are capable today of providing objective results that can guide and assist decision makers in implementing their future air pollution mitigation actions and developing urban/industrial development plans

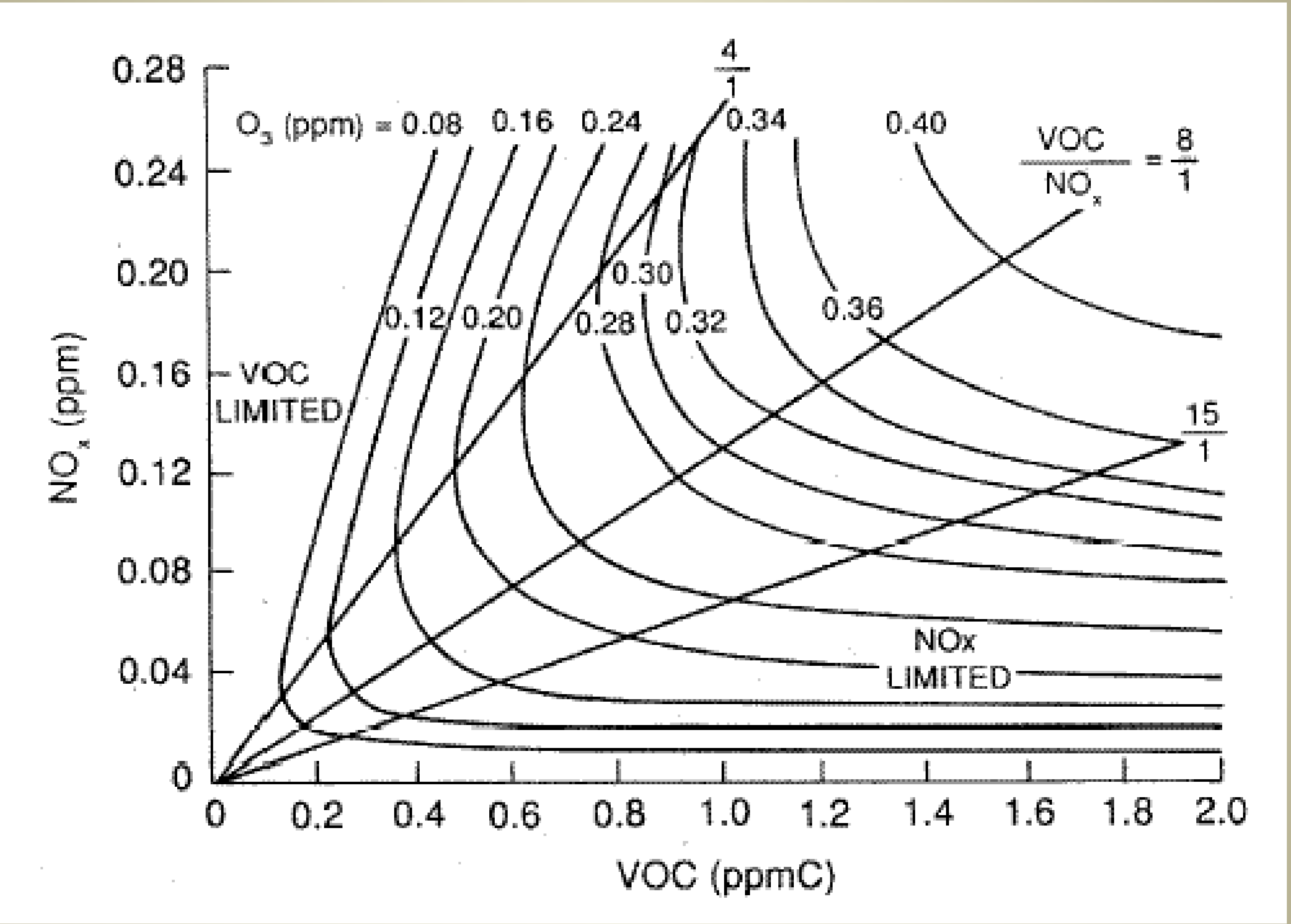
If This Approach is not Followed…

- Decision making will be subjective and incomplete and, unavoidably, affected by waste of resources and delay in solving the most pressing problems
- Long-term air pollution mitigation strategy should not be guided by fixed regulatory standards, but instead by today's advanced computer simulation tools
- This approach assures cost-effectiveness where, for every investment allocated to improve air quality, the efforts are channeled in the right directions, i.e. those that produce maximum benefit
- These problems are extremely complex and non-linear
- Only a set of well tested computerized tools can identify and provide optimal solutions producing
    - the maximum health and environmental benefits with fixed, pre-defined costs, or
    - the minimum costs for fixed, pre-defined benefits

The Challenge of Non-Linearity

- It is not a coincidence that the best improvements in the US were achieved for primary pollutants, like SO_2, CO, Pb
  - Linear relationship with emission rates
- Secondary pollutants (O_3, secondary fraction of $PM_{2.5}$) are more difficult
  - Precursors → O_3, $PM_{2.5}$
  - Decrease in emissions of precursors (e.g., NO_x, VOC, SO_2) does not assure proportional decrease of O_3, $PM_{2.5}$

Challenge: Non-Linearity (e.g. Ozone)



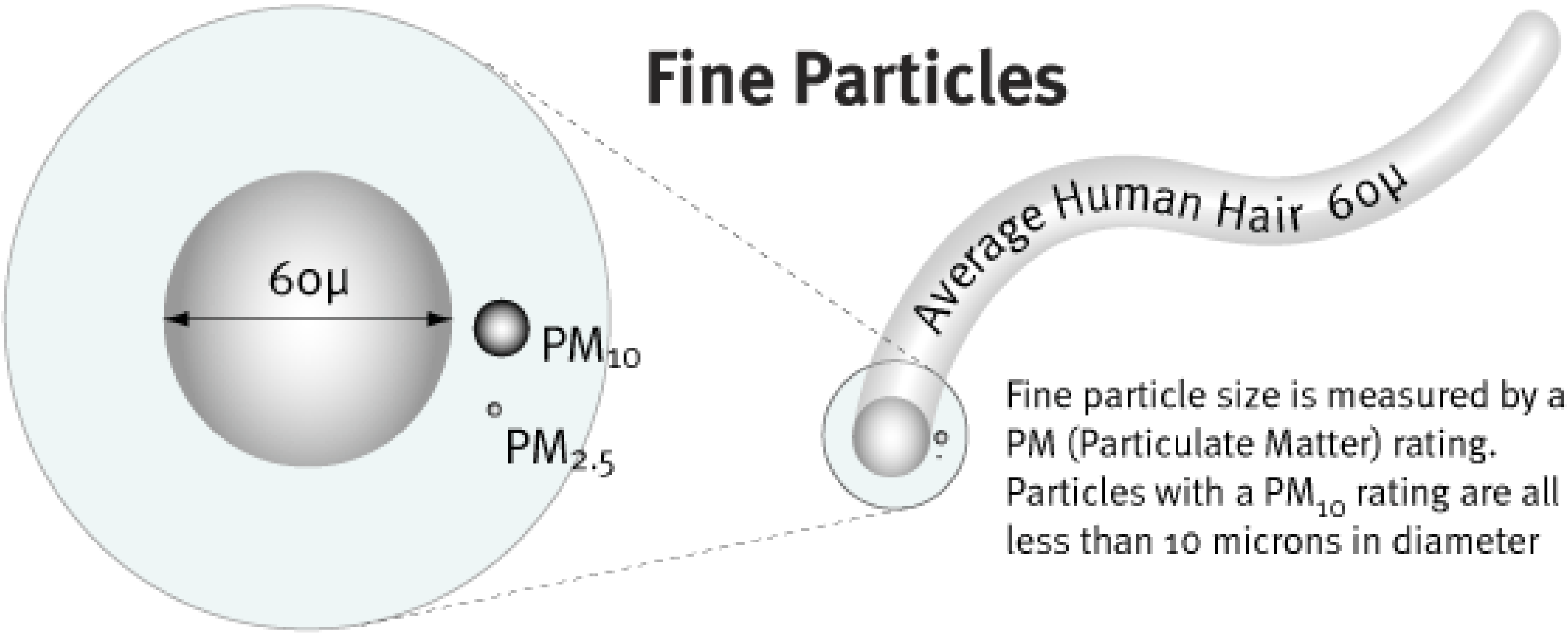
Empirical kinetic modeling approach (EKMA) diagram. SOURCE: NRC 1991, adapted from Dodge 1977.

Ozone Challenge

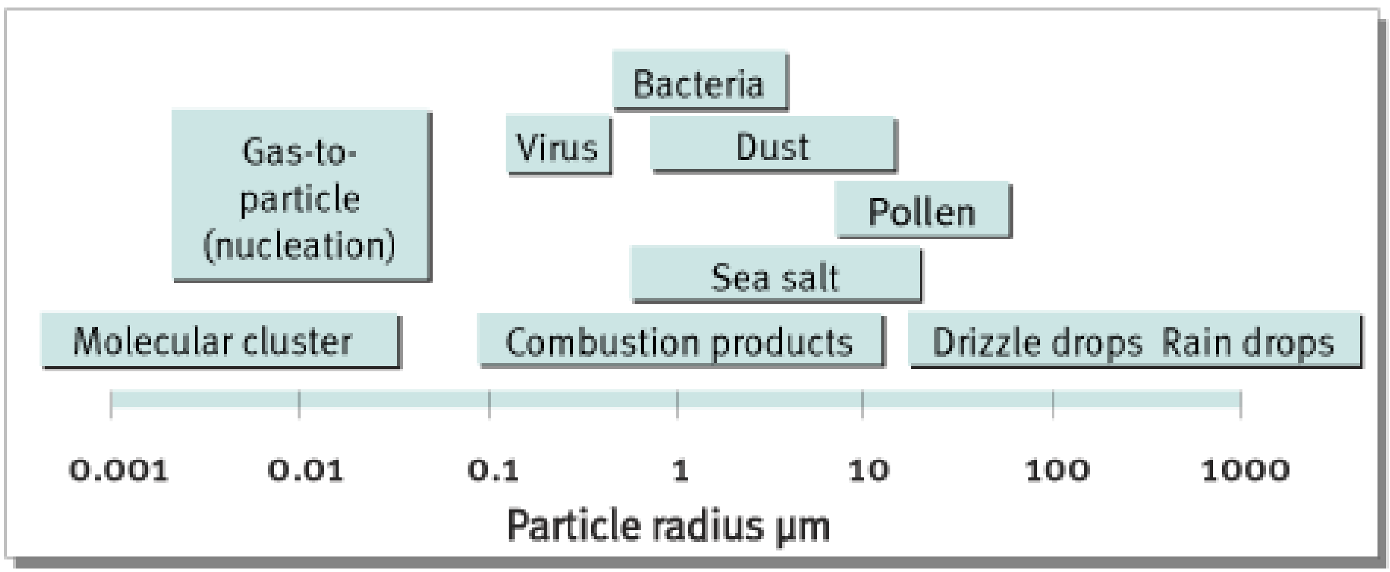
After we design and implement costly emission reduction strategies for the ozone precursors (VOCs and NO_x) emitted by anthropogenic sources, we may still achieve a very limited reduction of ozone. In fact, advanced computer modeling shows that

- some emission reduction strategies in "NO_x-limited" regions may produce no change at all in ozone concentrations, and paradoxically,
- some strategies in "VOC-limited" regions may even cause an increase in ozone concentrations.

Fine Particles



Fine particle size is measured by a PM (Particulate Matter) rating. Particles with a PM_{10} rating are all less than 10 microns in diameter



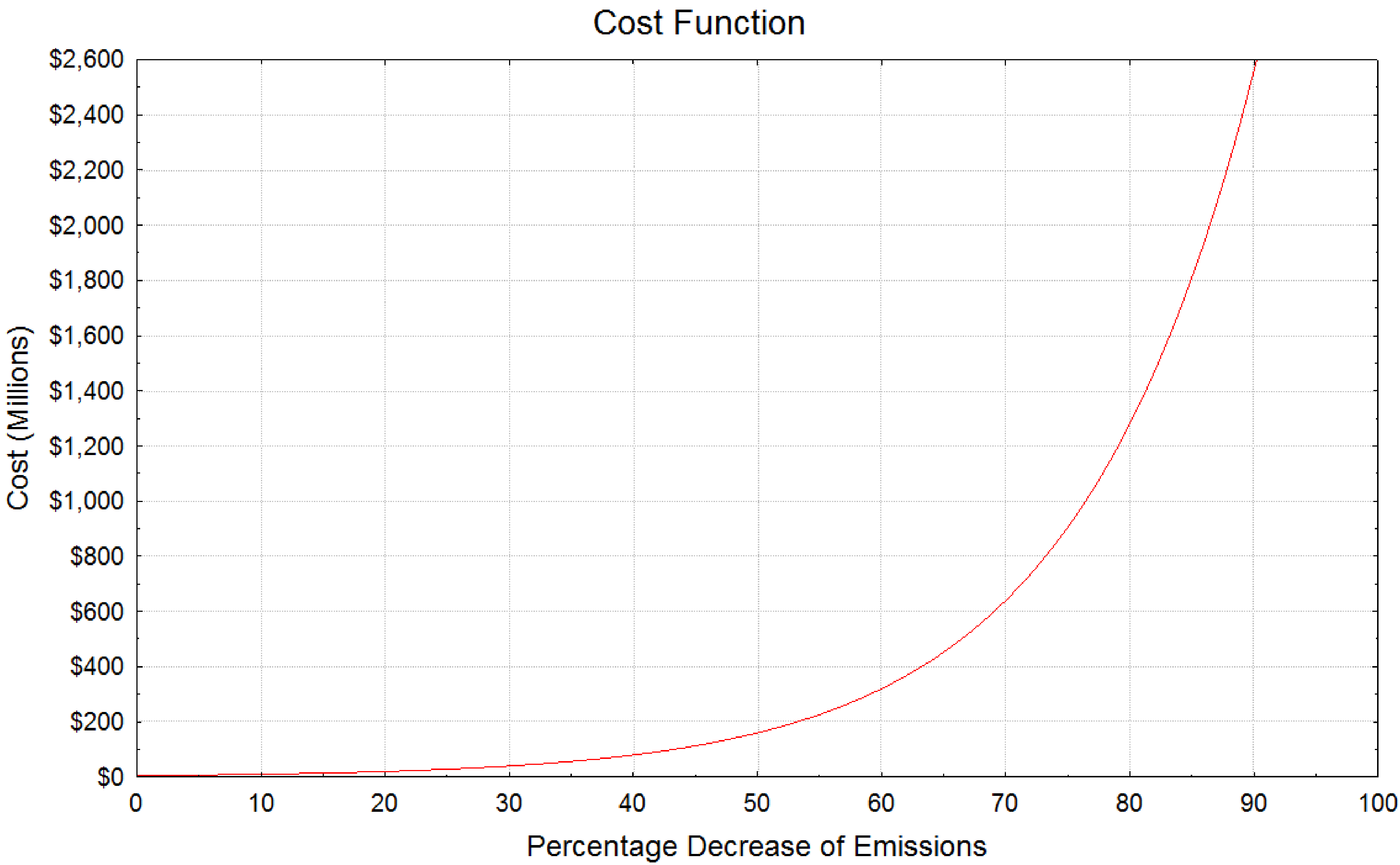
Queensland Government
Environmental Protection Agency

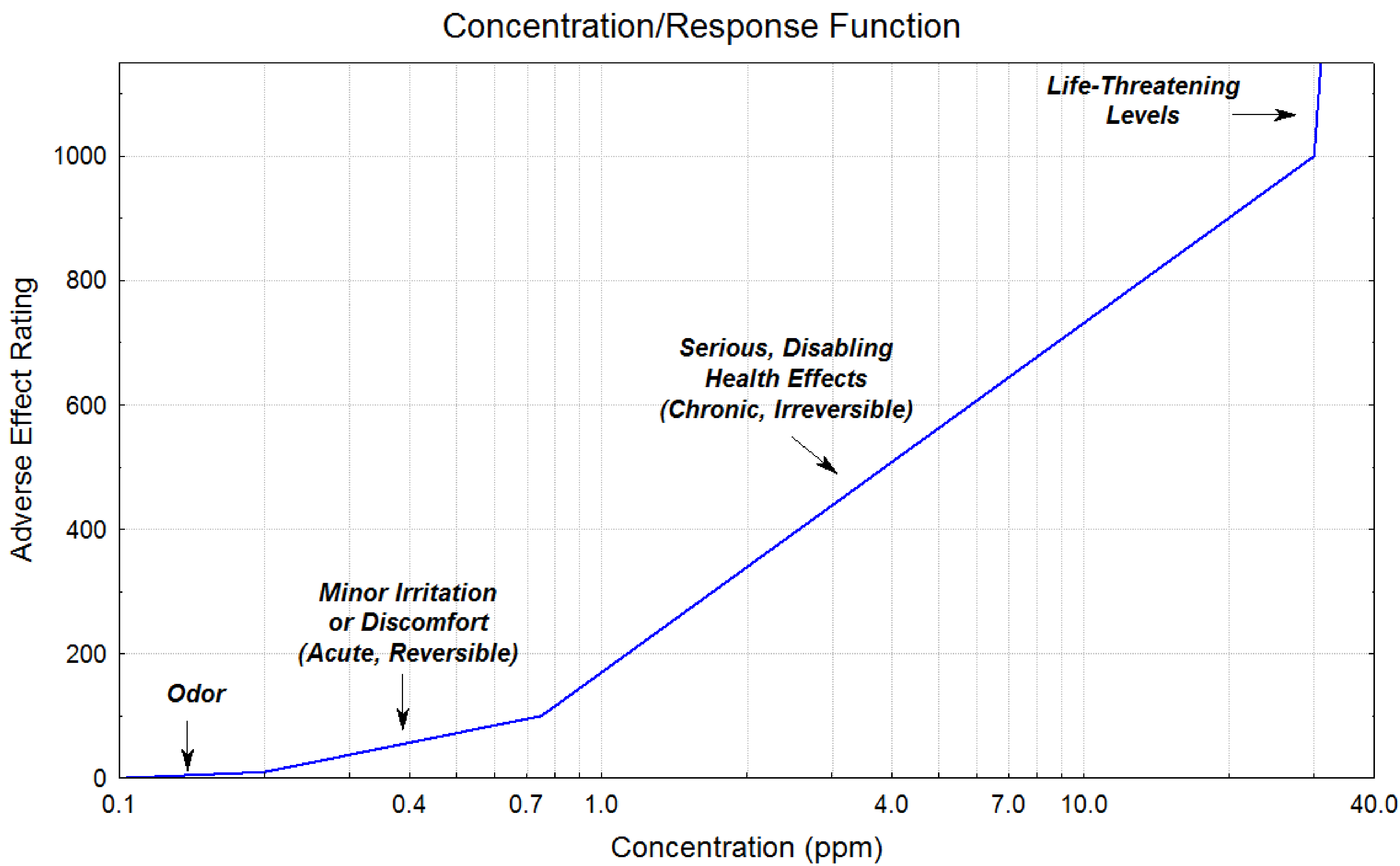
PM2.5 Challenge

- Recent (January 2013) air pollution episodes in Beijing, China, have been characterized by very unhealthy ambient concentrations of $PM_{2.5}$ of 900 μg/m^3. See:
  - http://www.forbes.com/sites/jackperkowski/2013/01/21/air-quality-in-china/
- These values are more than an order of magnitude greater than $PM_{2.5}$ air quality standards in Europe and North America (e.g., see: http://www.epa.gov/air/criteria.html)

Example

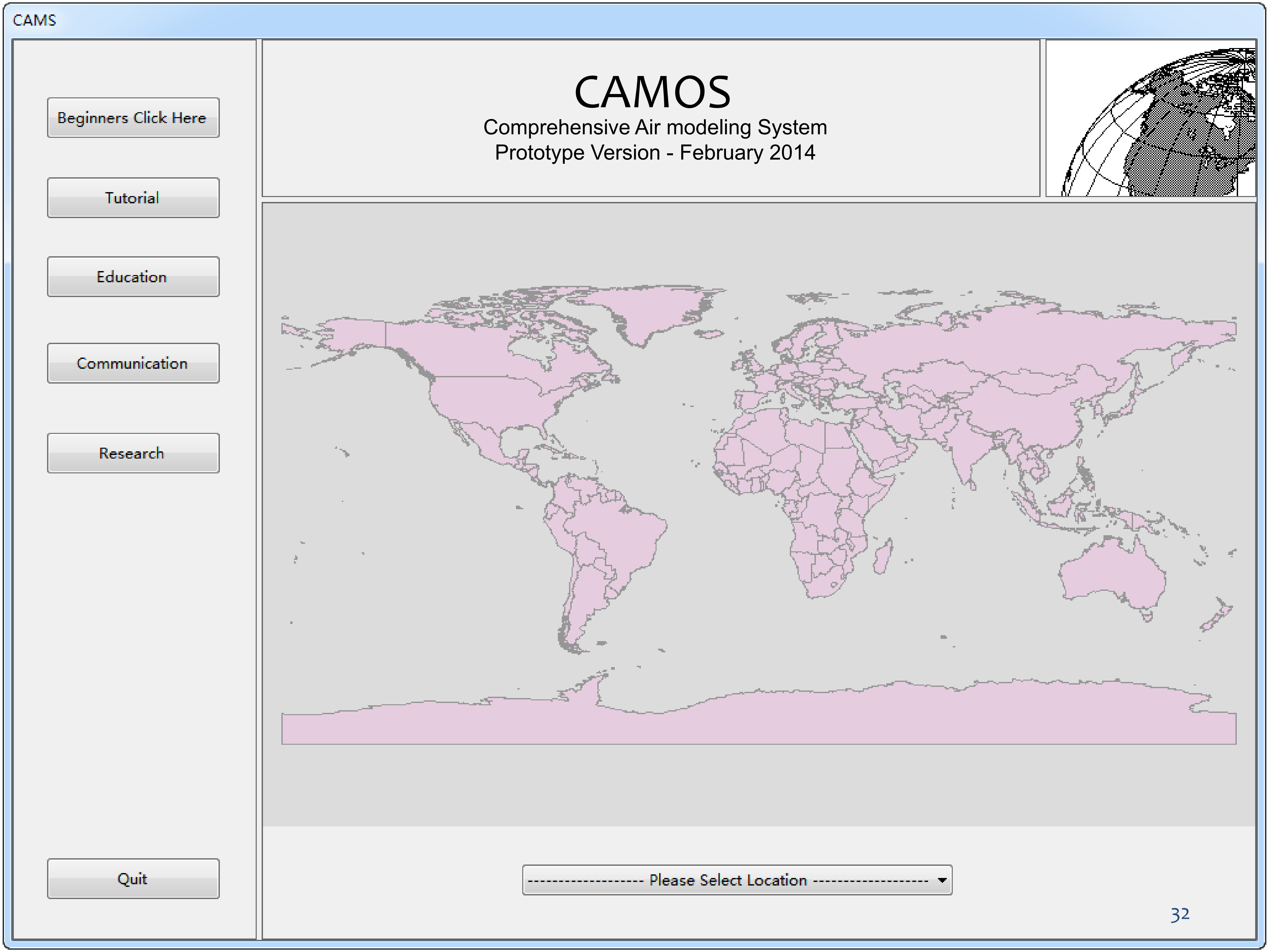
- 10 B$ are allocated to improve air quality in the Shanghai region of China
- Can we spend them wisely? E.g. to maximize public health?
- In theory yes, but …
  - Team
  - Data collection
  - Modeling: CALPUFF, CAMx, …
  - Δ$ ➔ΔE ➔ ΔC ➔ ΔHB … All non-linear
  - Maybe a year later we have an "optimal" investment plan
  - Results difficult to re-utilize in another region


Cost Function
Cost (Millions)
$2,600
$2,400
$2,200
$2,000
$1,800
$1,600
$1,400
$1,200
$1,000
$800
$600
$400
$200
$0
0
10
20
30
40
50
60
70
80
90
100
Percentage Decrease of Emissions


Concentration/Response Function
Life-Threatening
Levels
Serious, Disabling
Health Effects
(Chronic, Irreversible)
Minor Irritation
or Discomfort
(Acute, Reversible)
Odor
Adverse Effect Rating
1000
800
600
400
200
0
0.1
0.4
0.7
1.0
4.0
7.0
10.0
40.0
Concentration (ppm)

Conceptual Design

- We envision the development of a series of interacting software modules that the user can access through a user-friendly GUI on a PC Microsoft Windows-based computer platform
- The software system will be installed on our own Servers and made available to authorized users as a Web-Application
- We call it Comprehensive Air Modeling/Optimization System (CAMOS)
- Authorized users will be able to access the system with user name/password at the site www.camos.co (just activated for demo purposes)


CAMS
CAMOS
Comprehensive Air modeling System
Prototype Version - February 2014
Beginners Click Here
Tutorial
Education
Communication
Research
Quit
------------------ Please Select Location ------------------

frmCostFunctions

Cost functions

For each source category the cost of the emission reduction is calculated with the following expression: Cost = A*(DE) + B*(DE)^P Where cost must result in M$, and DE is the percent emission reduction.

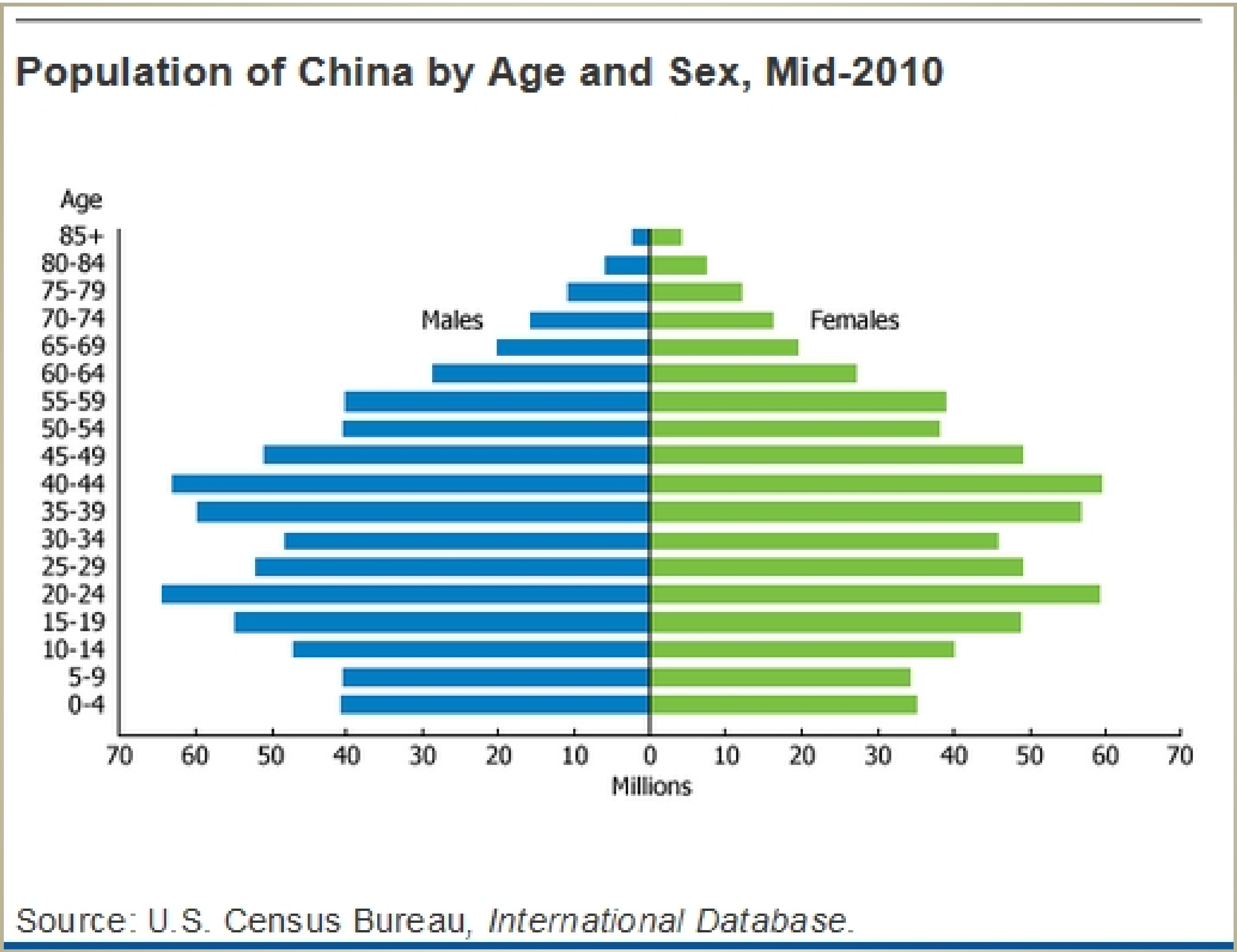
Cost functions coefficients

Category	A	B	P
Mobile	1	0.4	0.2
Area	3	0.1	1.5
Power_plants	0.5	0.5	2
High_stacks	1.2	0.8	2.3
Low_stacks	0.9	0.4	1.9

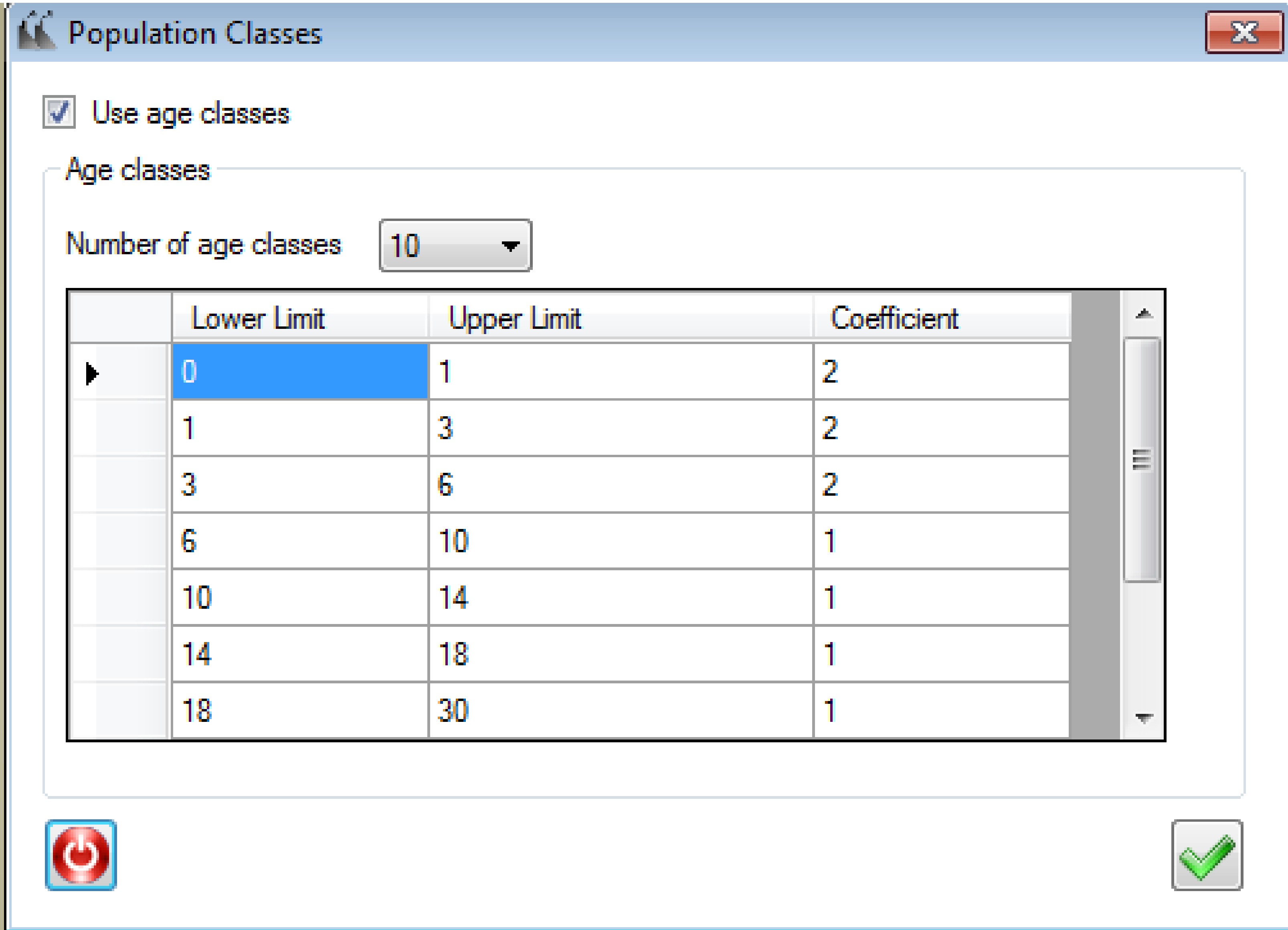
Cost Functions

Benefit Functions

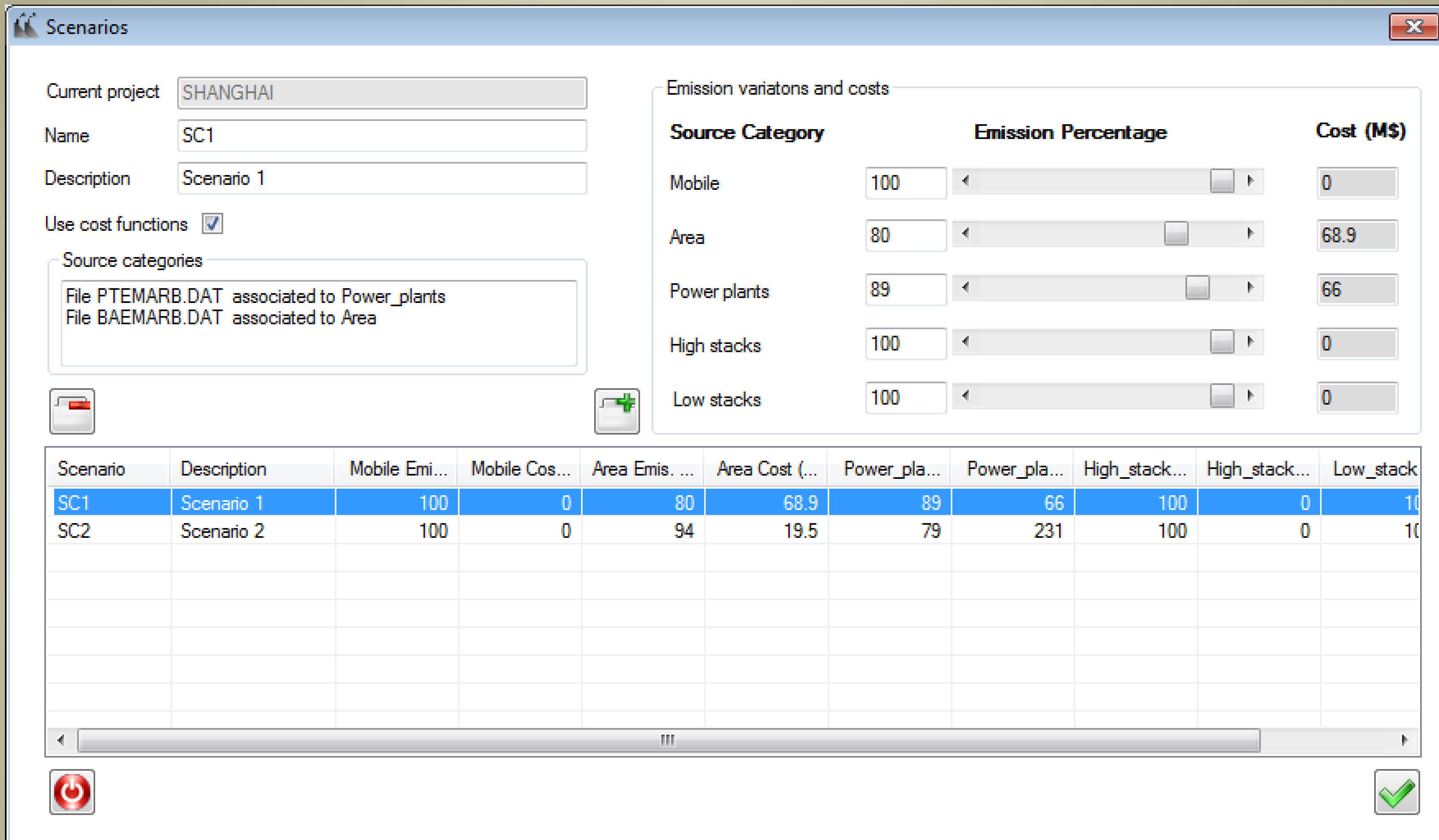
- Benefits are calculated in each cell of the modeling domain, as a function of the concentration reductions, multiplied by the density of population
- Additional benefits are calculated at “special interest” receptor locations (e.g., schools, hospitals)



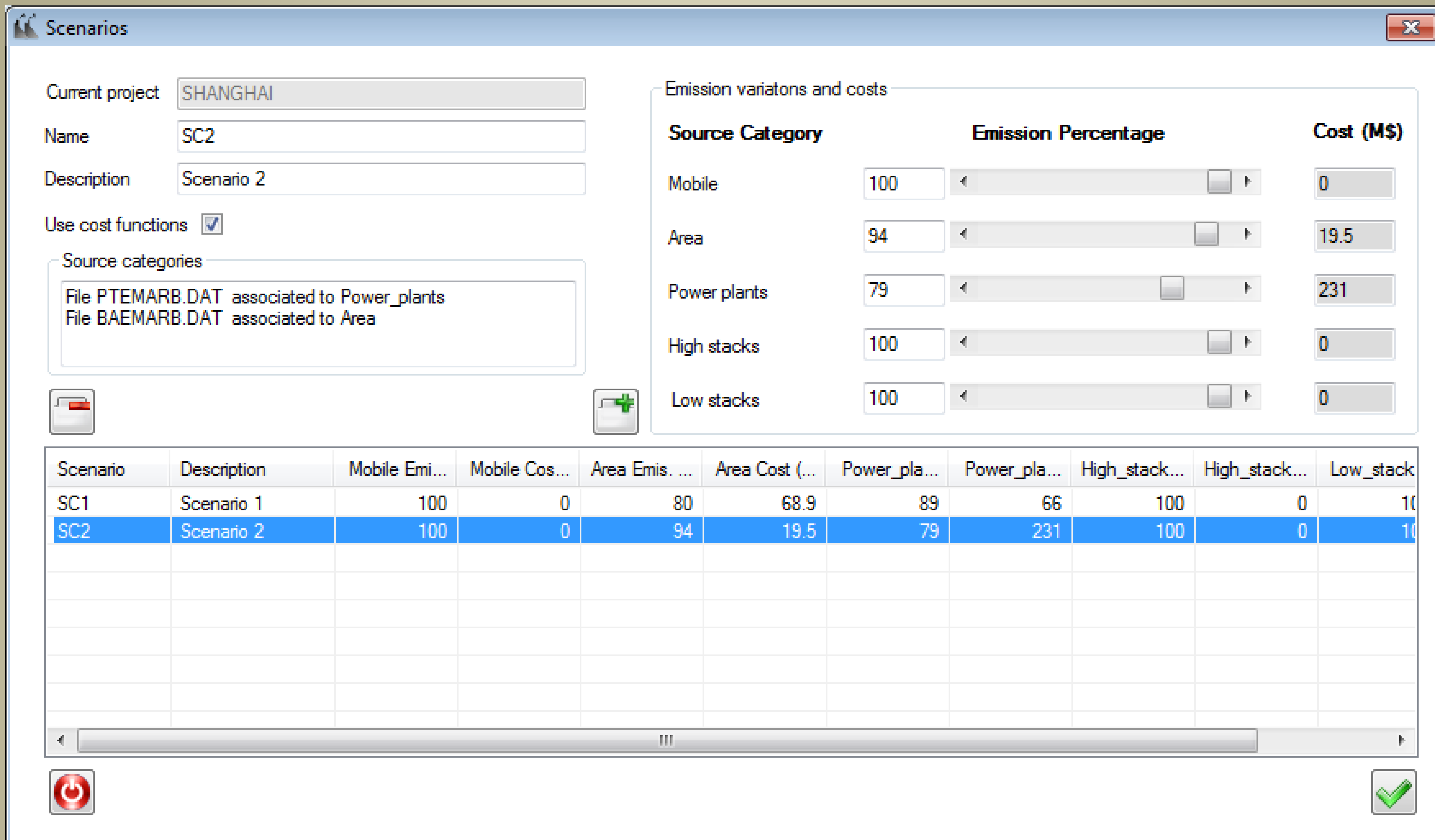
Population Distribution - China



Population Classes
and Weights

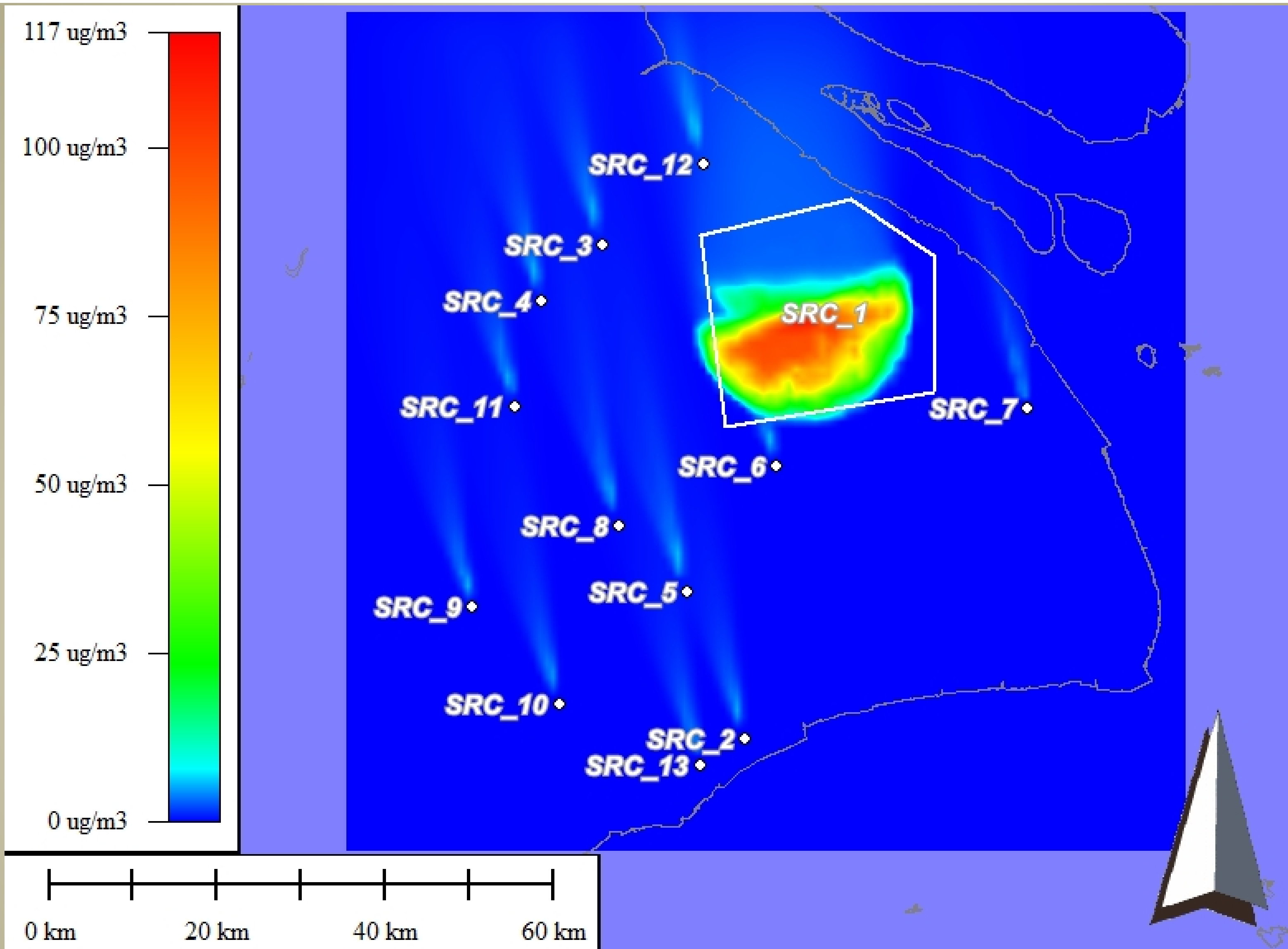


Modify SO_2 Emission Scenarios by adjusting Base Case: Scenario 1

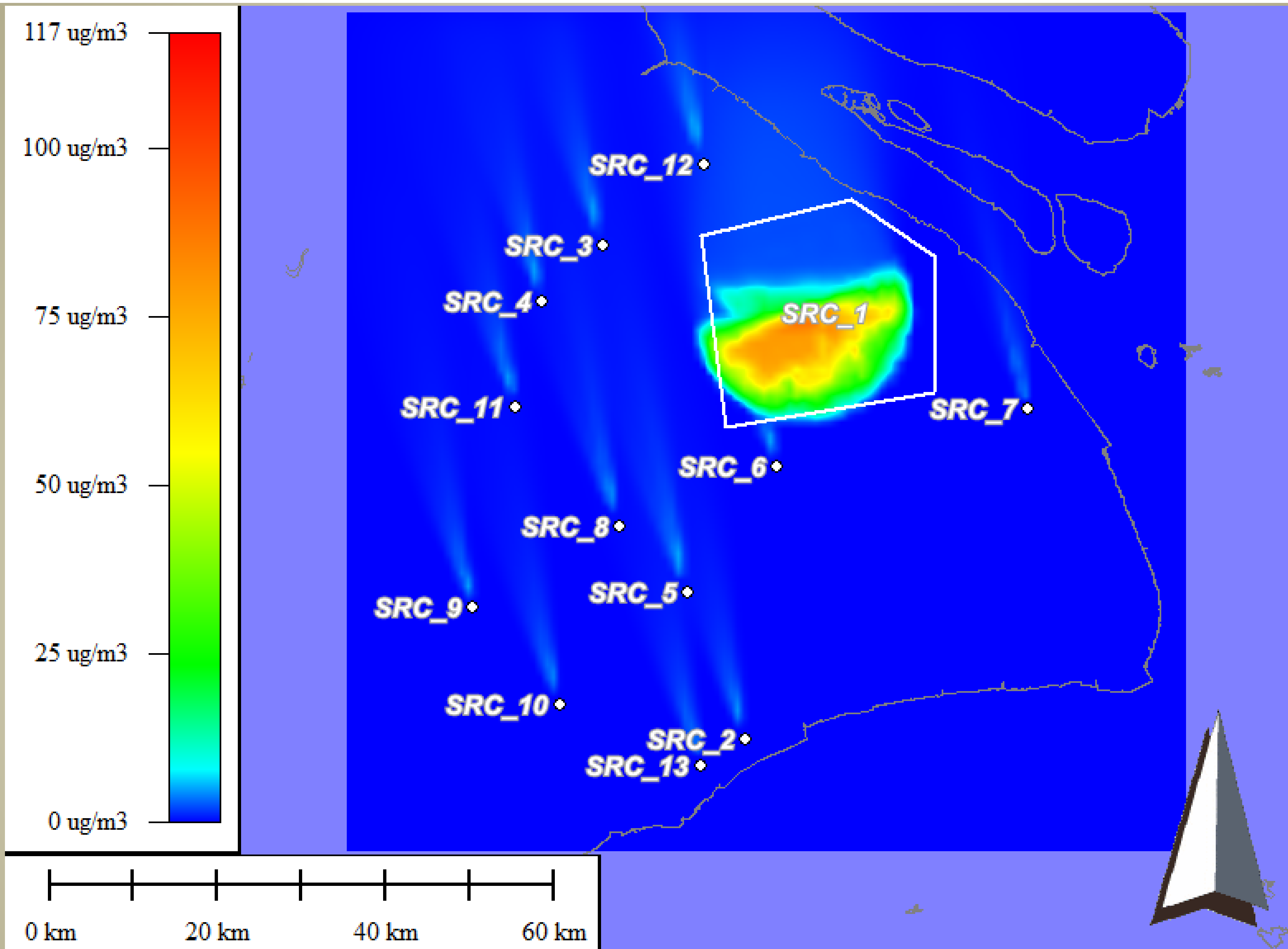


Modify SO_2 Emission Scenarios
by adjusting Base Case:
Scenario 2

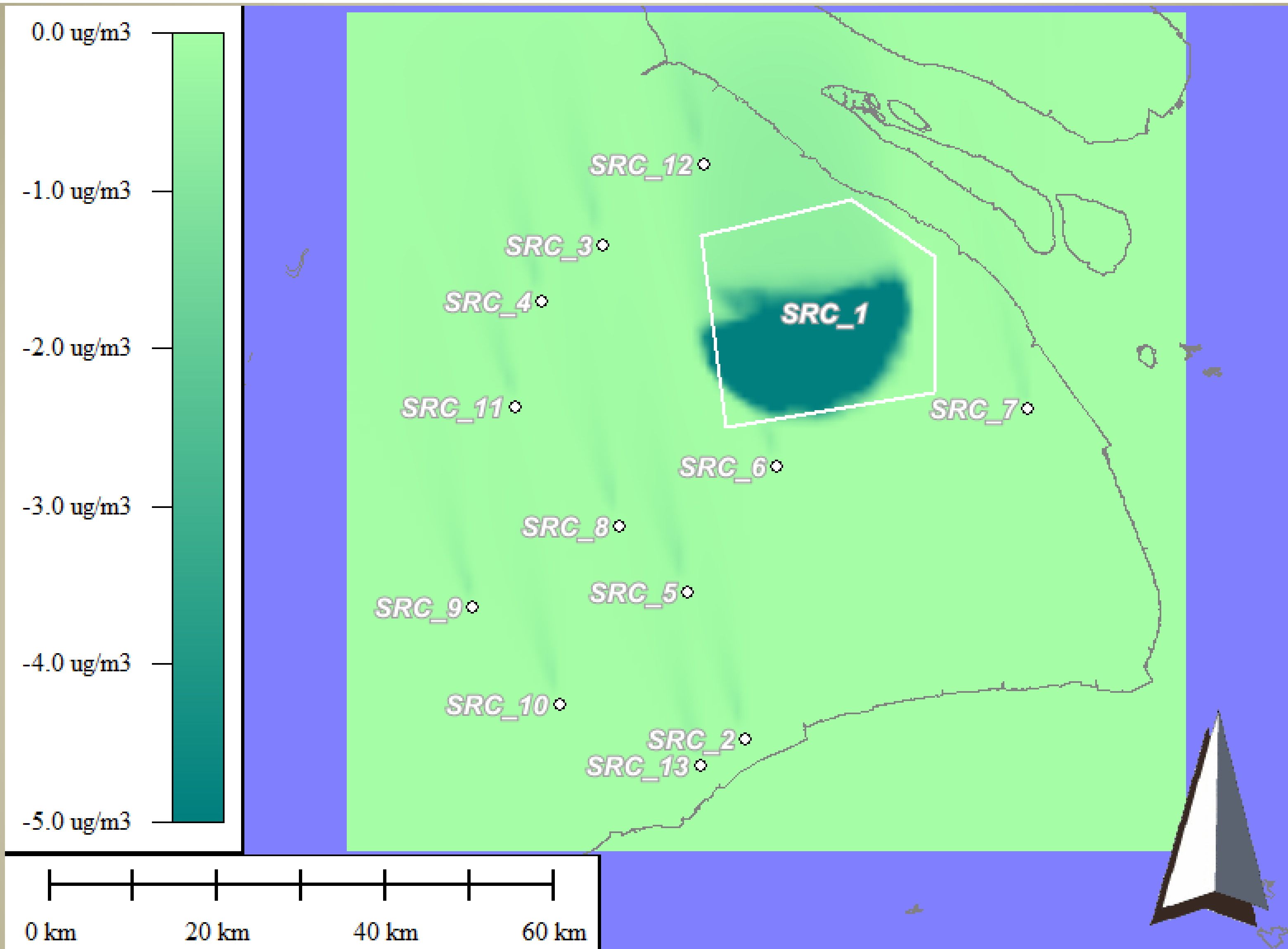
Zoom-In to Shanghai, China



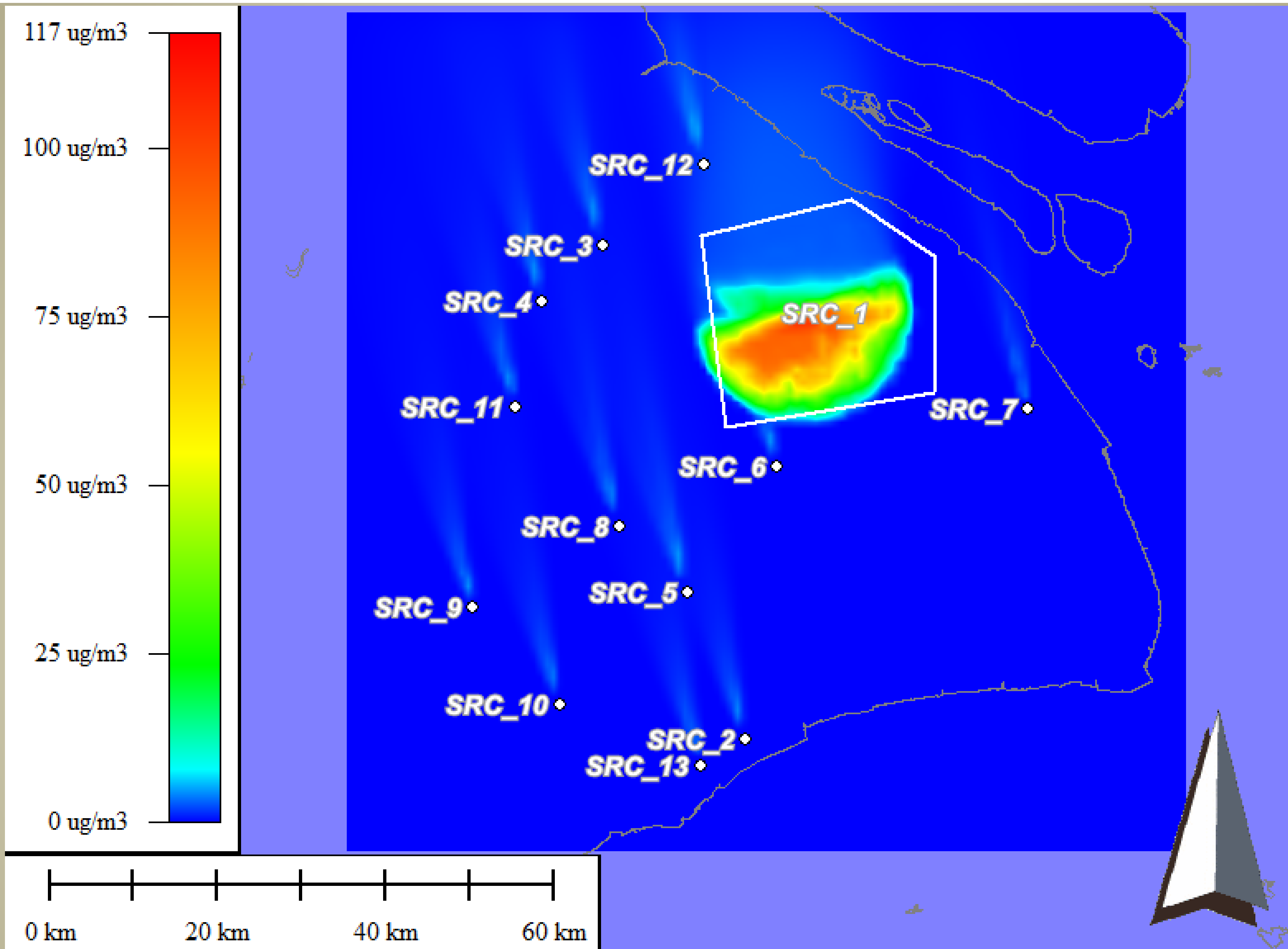
Base Case: SO_2 Emissions
(12 Hour SO_2 Concentrations)



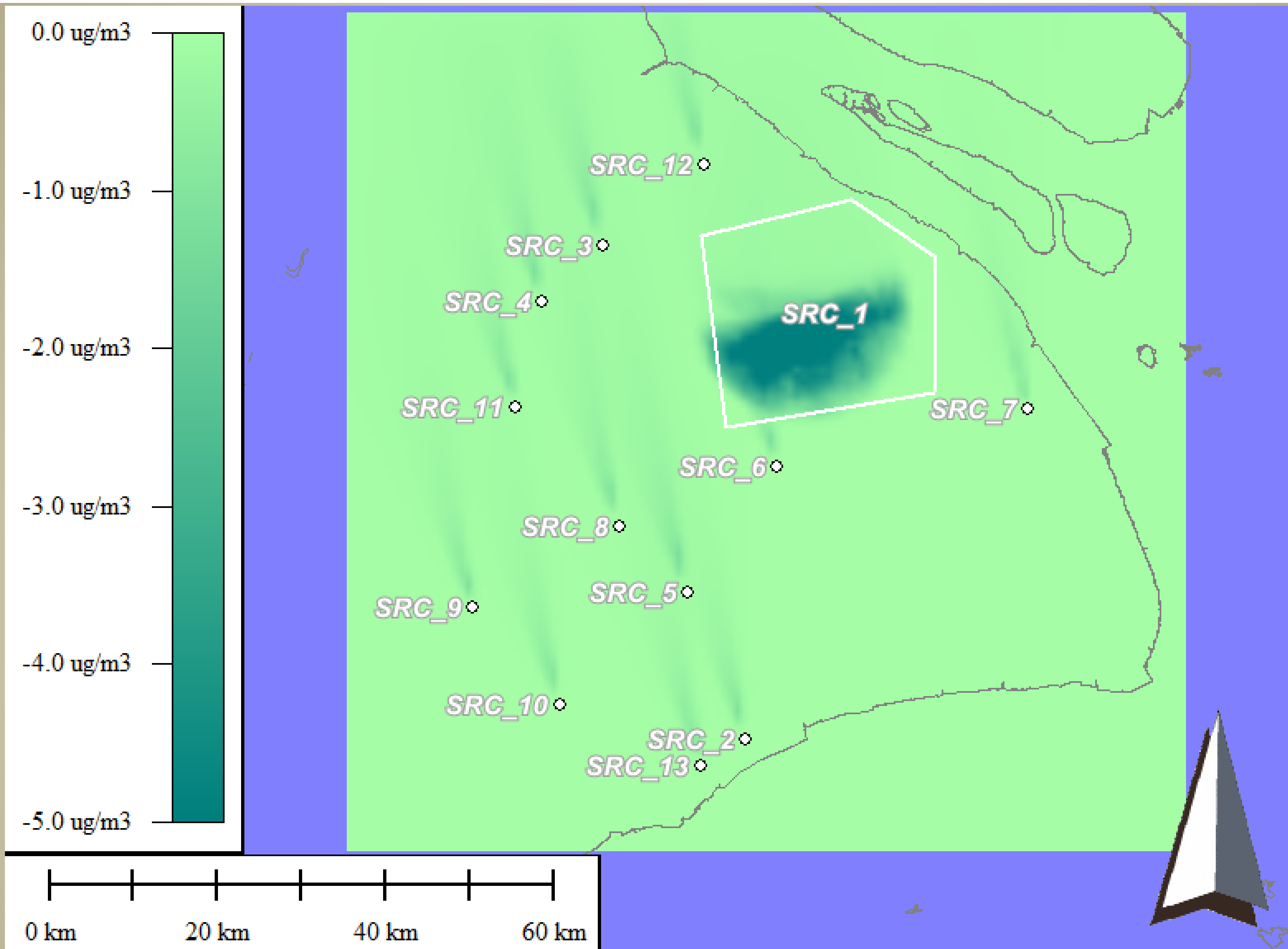
Scenario 1: Reduced SO_2 Emissions
(12 Hour SO_2 Concentrations)



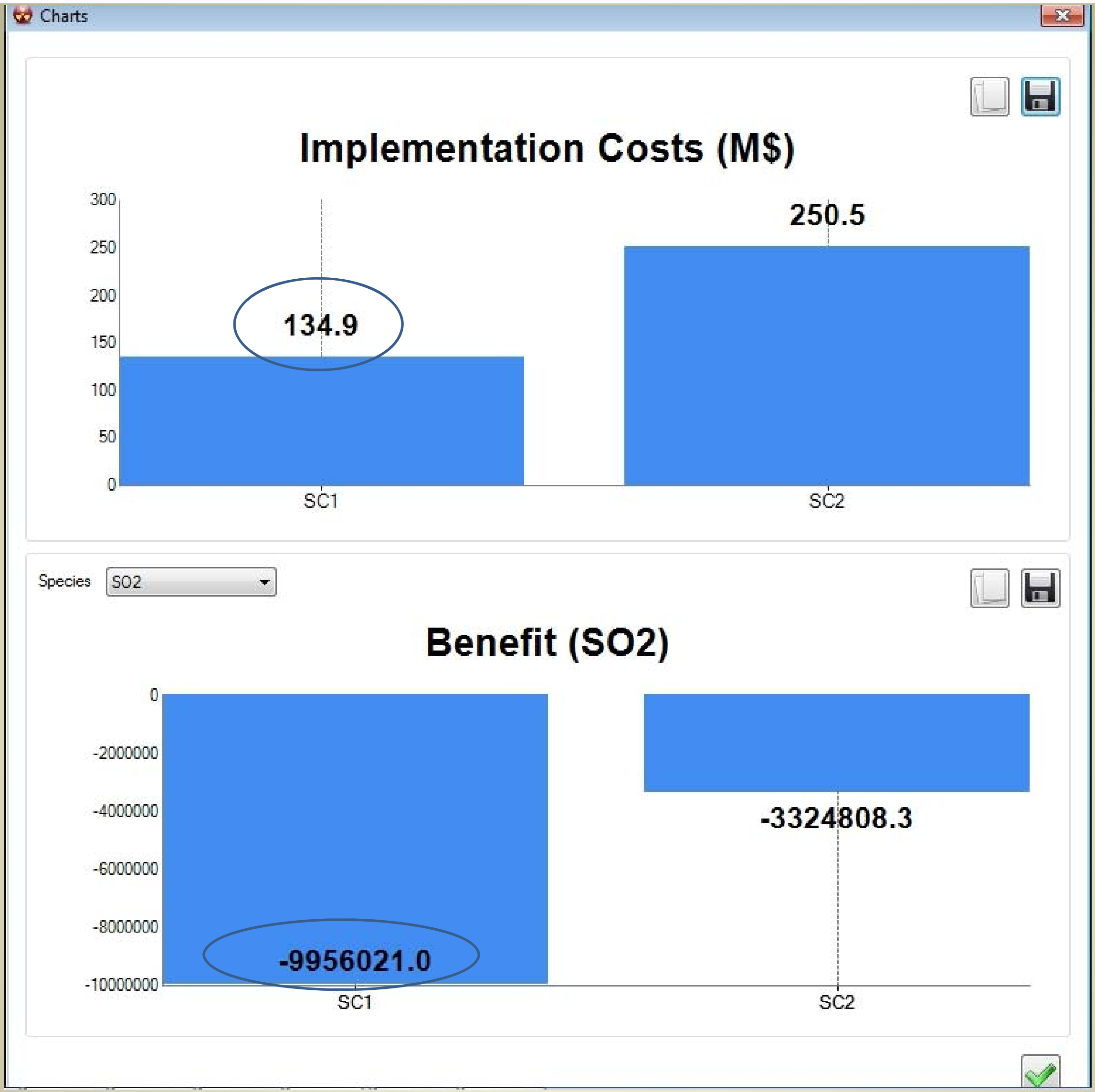
Scenario 1: SO_2 Difference from Base Case
(12 Hour "Delta" SO_2 Concentrations)



Scenario 2: Reduced SO_2 Emissions
(12 Hour SO_2 Concentrations)



Scenario 2: SO_2 Difference from Base Case
(12 Hour "Delta" SO_2 Concentrations)



By combining gridded Differences with Population Density and Age Weights, Scenario 1 has less Cost, but greater benefit (lower SO_2 impact over the Population)

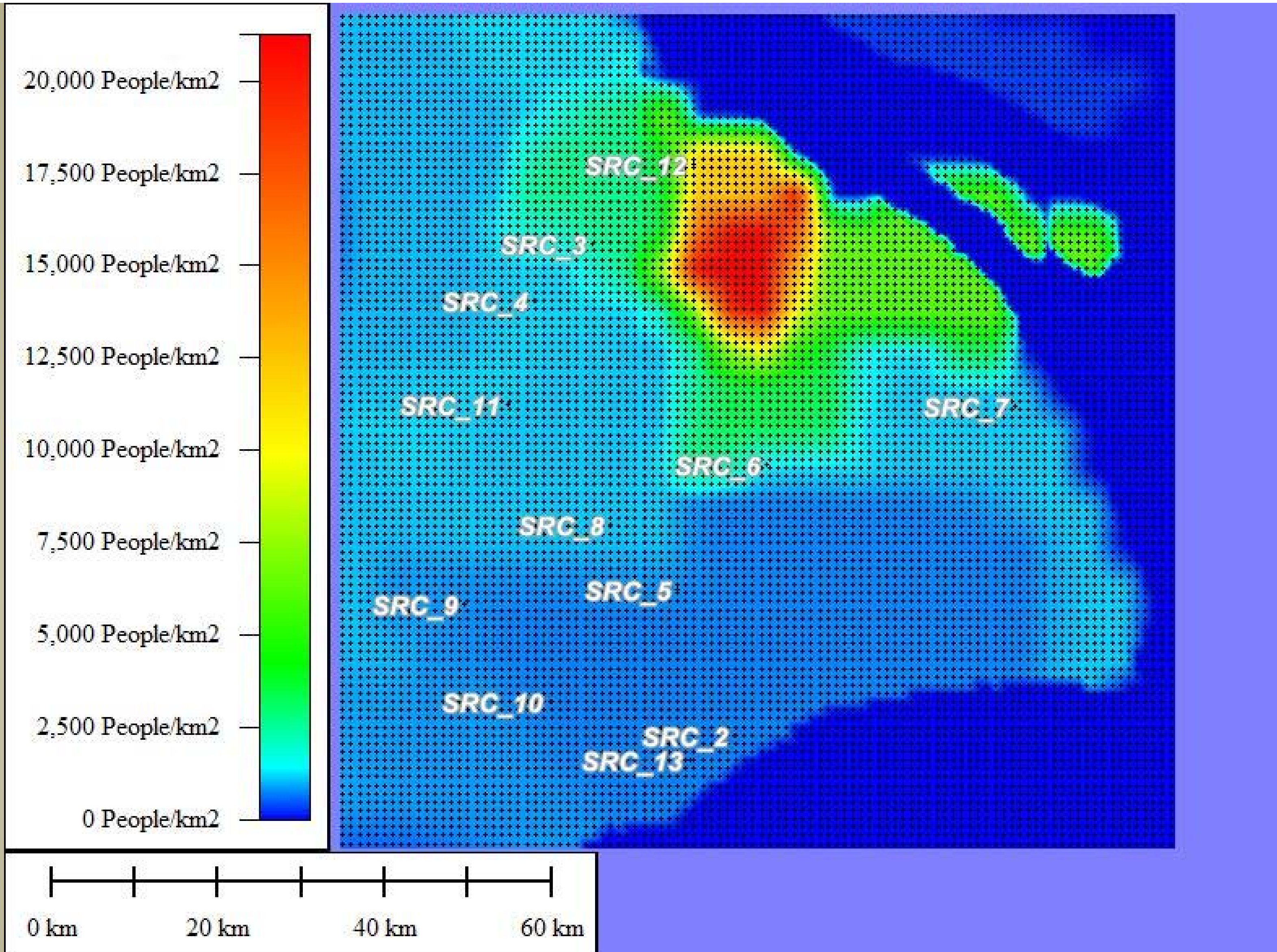
Sulfate (SO_4) Simulation

Power Plant Scenarios,
Costs, and Benefits

3-Day Simulation (~15-min PC simulation)
April 2-4, 2012

SO_2 to SO_4 Chemistry

- Complex set of reactions
- Role of photochemistry
- Role of meteorology (relative humidity)
- In-cloud chemistry
- A typical value: 1% gas SO_2 is converted to SO_4 fine particles over 1 hour



- **Shanghai Population Density**
- **CALPUFF 1-km grid (100km by 100km)**
- **12 point sources (power plants)**

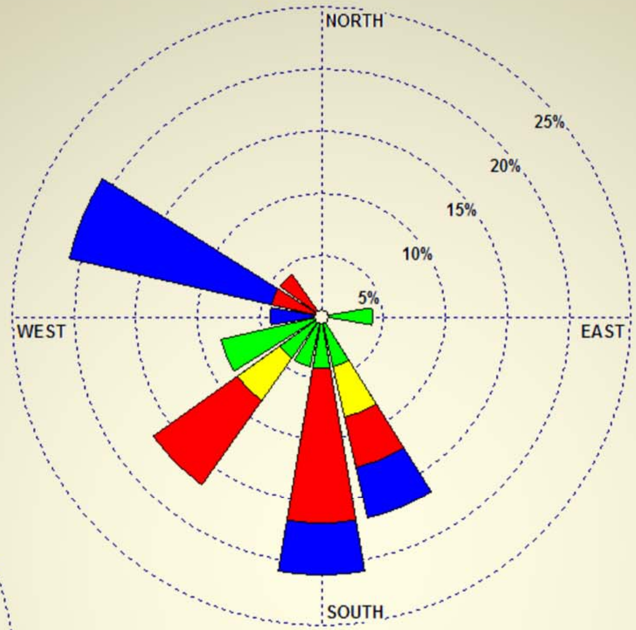
12 Power Plant Point Sources (simplified input)

Stack height: 75 m
Stack Diameter: 3 m
Exit Velocity: 10 m/s

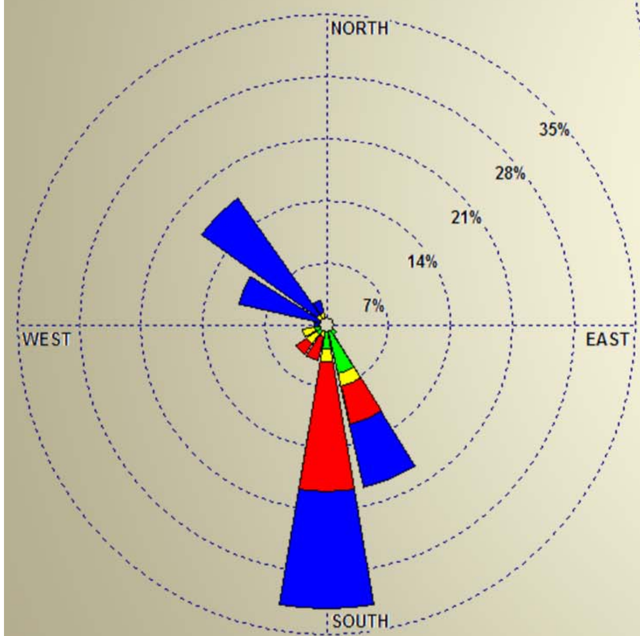
Power Output of each source: 2,500 MW

SO_2 baseline emission rate of each source: 1,200 g/s

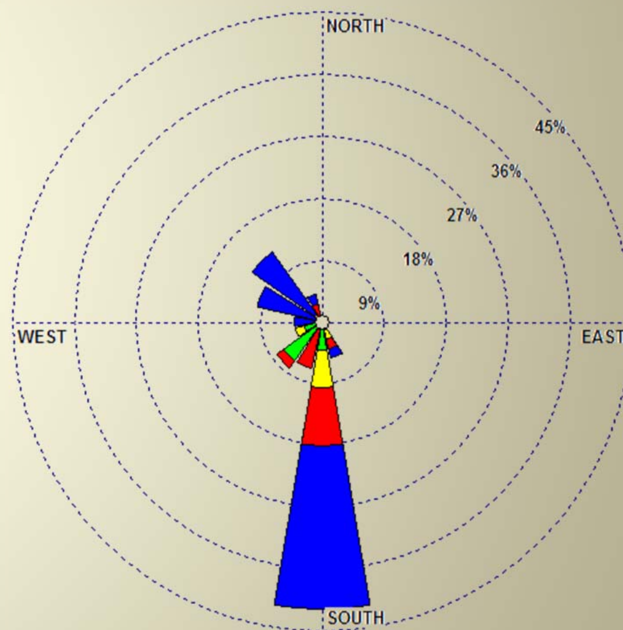
Wind Roses for April 2-4, 2010 (direction from)



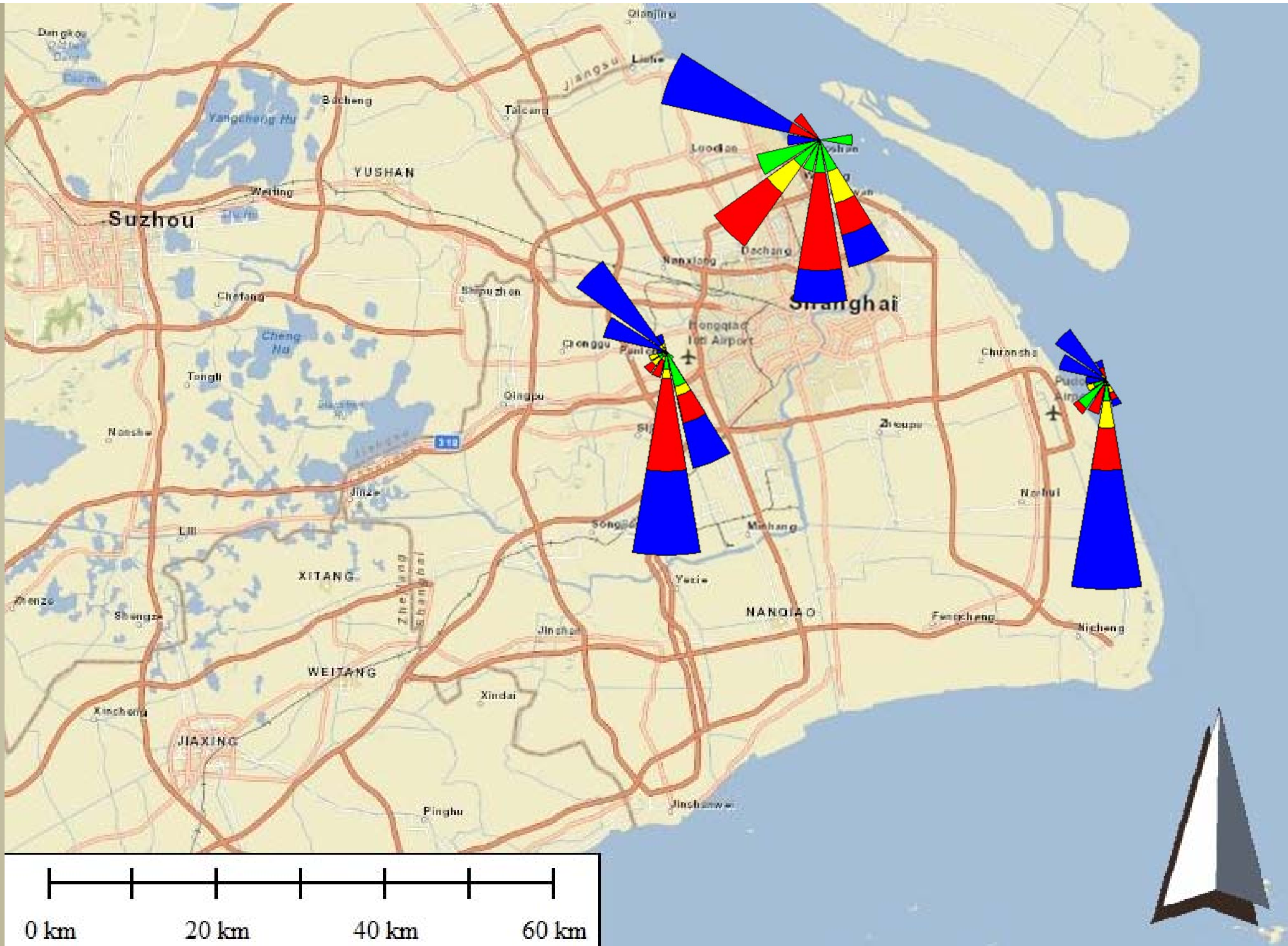
Shanghai Station
Average Wind Speed:
8.4 knots
Calms: 0%



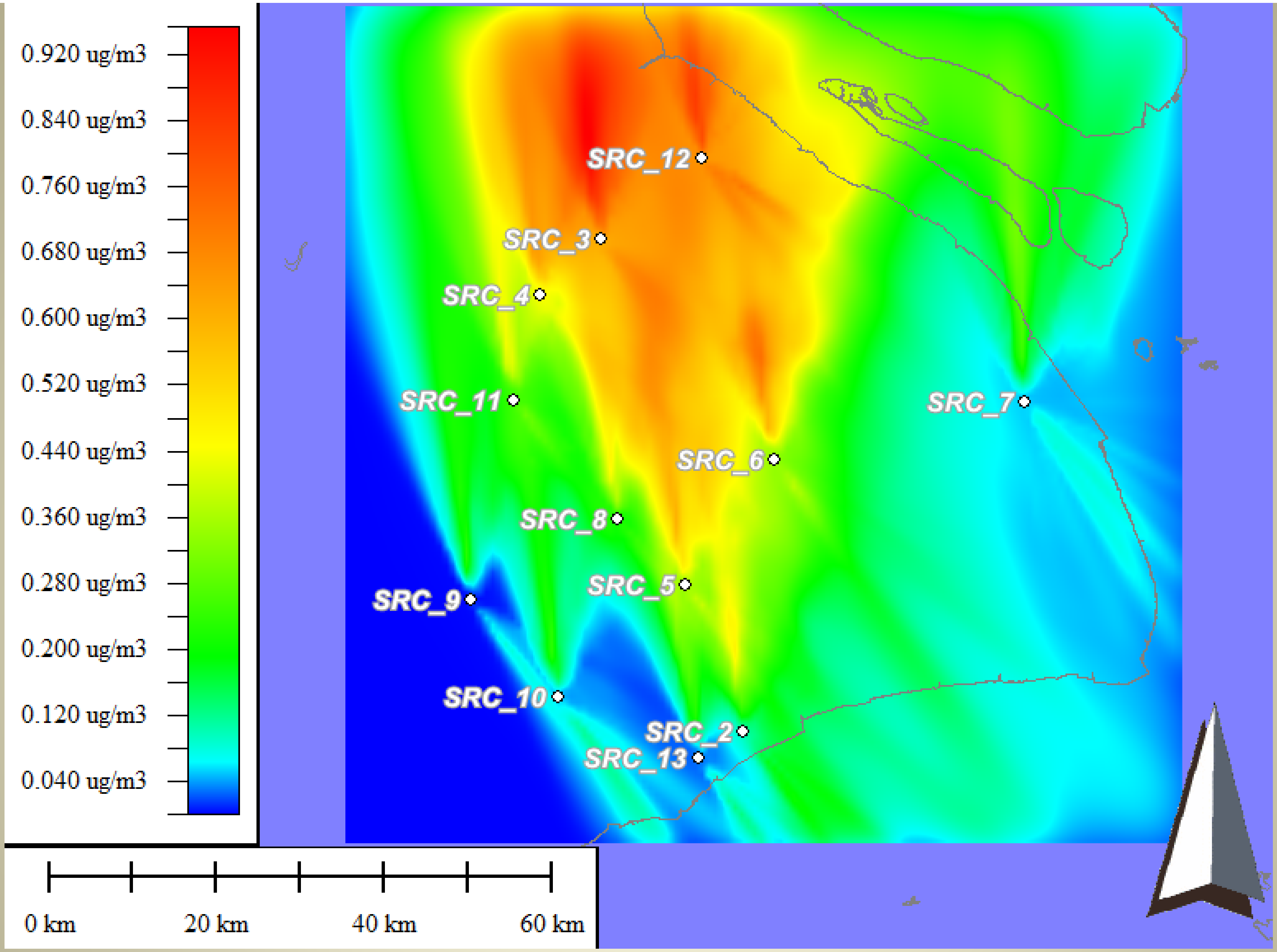
Hongqiao Airport
Average Wind Speed:
10.8 knots
Calms: 4.1%



Pudong Airport
Average Wind Speed:
12 knots
Calms: 2.7%



Prevailing Winds in Shanghai Area
for April 2-4, 2010



3-day baseline CALPUFF SO_2 Emissions (72 hours)
Plot 3-day average baseline SO_4 concentrations

Some Possible Relationships of Health Cases and Costs to Sulfate Concentrations

Estimated annual probability per person per 1 μg/m³ change in Annual SO_4 Concentrations (middle values)	Abbreviation	Health Case Name	Relative Cost Index
3.50E-05	PM	Premature Mortality	220,346
6.60E-05	CB	Chronic Bronchitis	29,381
1.60E-05	RHA	Respiratory Hospital Admission	1,042
1.30E-05	CHA	Cardiac Hospital Admission	1,042
9.30E-05	RAD	Restricted Activity Day	8.5
3.10E-02	ASD	Asthma Symptom Day	3.2
9.30E-05	LRSD	Lower Respiratory Symptom Day	1

(*) These values are adapted from 1997 China data published in 2003 (Journal of Environmental Sciences vol 15 no 5 pp 611) and clearly underestimate today's costs

Example:

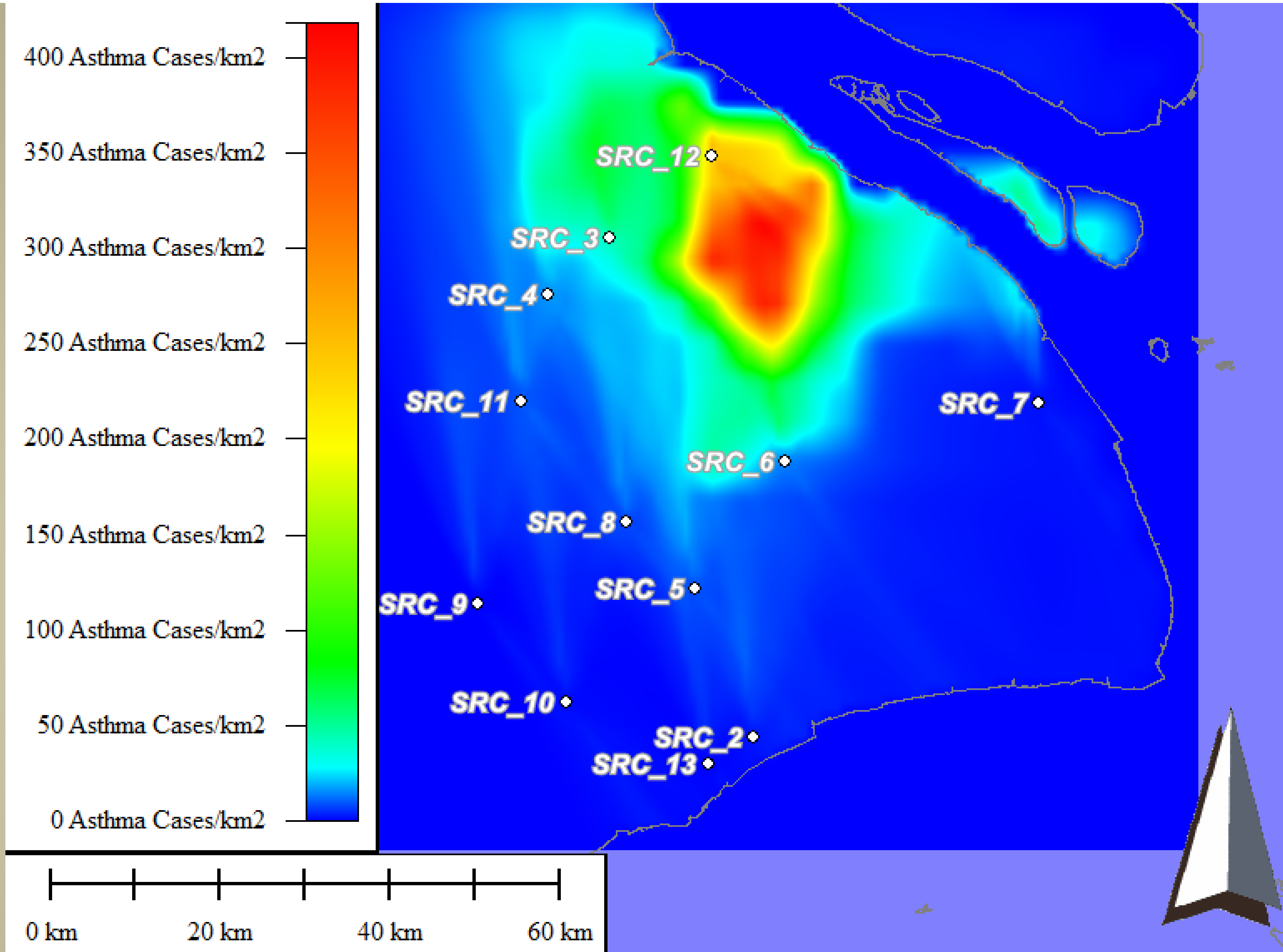
Estimate number of Asthma Symptoms and Relative Cost for one grid cell:

Grid cell population: 1,000
Grid cell average baseline SO_4 concentration: 0.5 μg/m^3

Estimated cases of Asthma Symptoms:
(1,000)*(0.5)*(0.031) = 15.5

Relative Cost Index due to Asthma Symptoms:
31*(3.2) = 49.6

Repeat analysis for all grid cells,
and all other Health Case types,
and calculate total cases and costs



Estimated Density of baseline Asthma Symptom Cases in CALPUFF Grid

	Premature Mortality PM	Chronic Bronchitis CB	Respiratory Hospital Admission RHA	Cardiac Hospital Admission CHA	Restricted Activity Day RAD	Asthma Symptom Day ASD	Lower Respiratory Symptom Day LRSD	Total	
Totals	220	415	101	82	585	195,112	585	**197,100**	**Health Cases**
Percent	0.0014%	0.0026%	0.0006%	0.0005%	0.0037%	1.2%	0.0037%	**1.3%**	**Percent of Population**
Cost	48,539,443	12,204,735	104,963	85,283	4,953	630,360	585	**61,570,323**	**Cost Index**

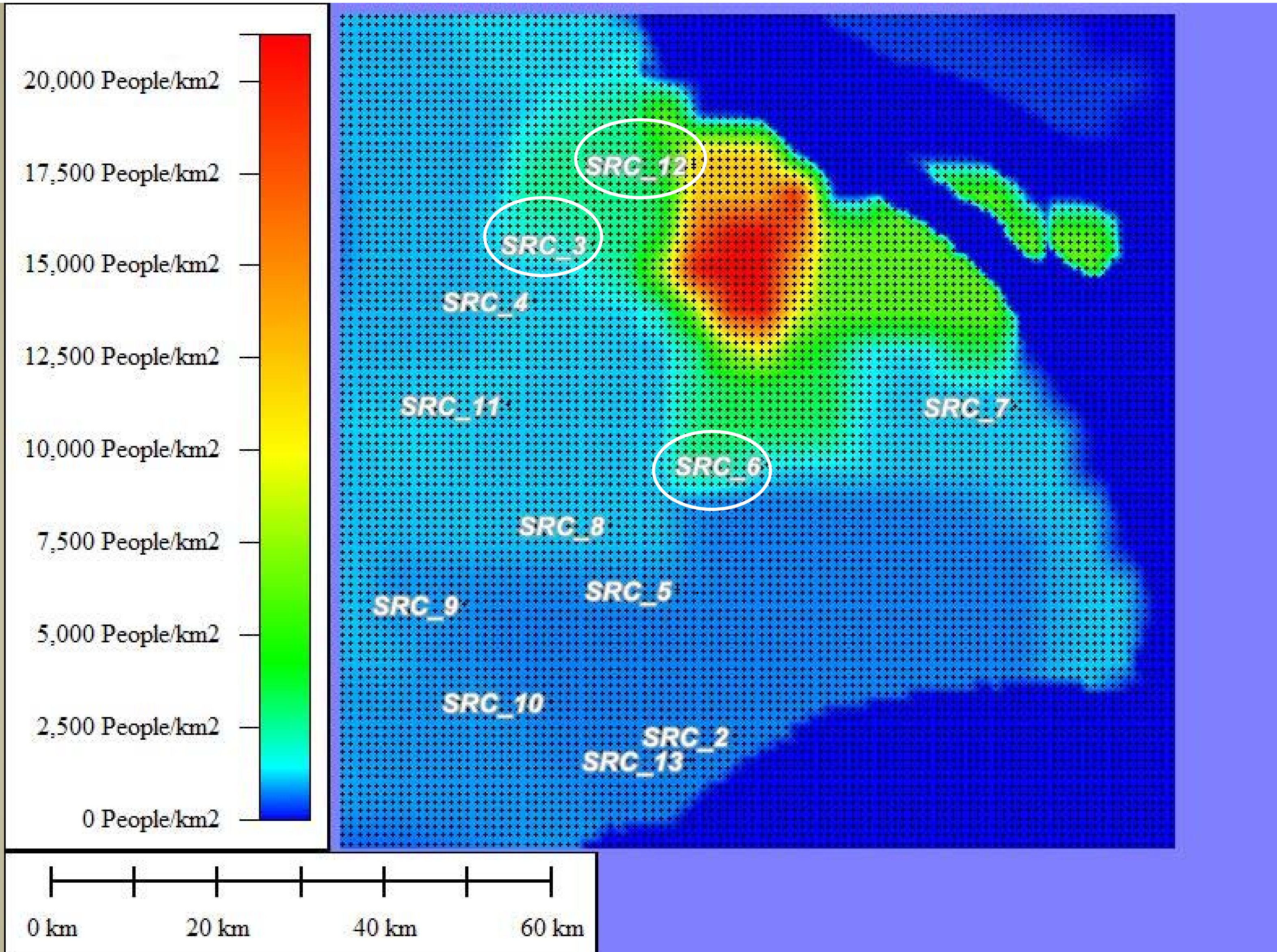
Baseline Health Cases and Costs due to Sulfate Concentrations (total population = 15,761,275)

Some Literature Information:

- **Cost of Installing Wet Scrubber:**
  ~ $200,000 per MW

- **Cost of Installing Wet Scrubber for one 2,500 MW power plant:**
  ~ $500,000,000

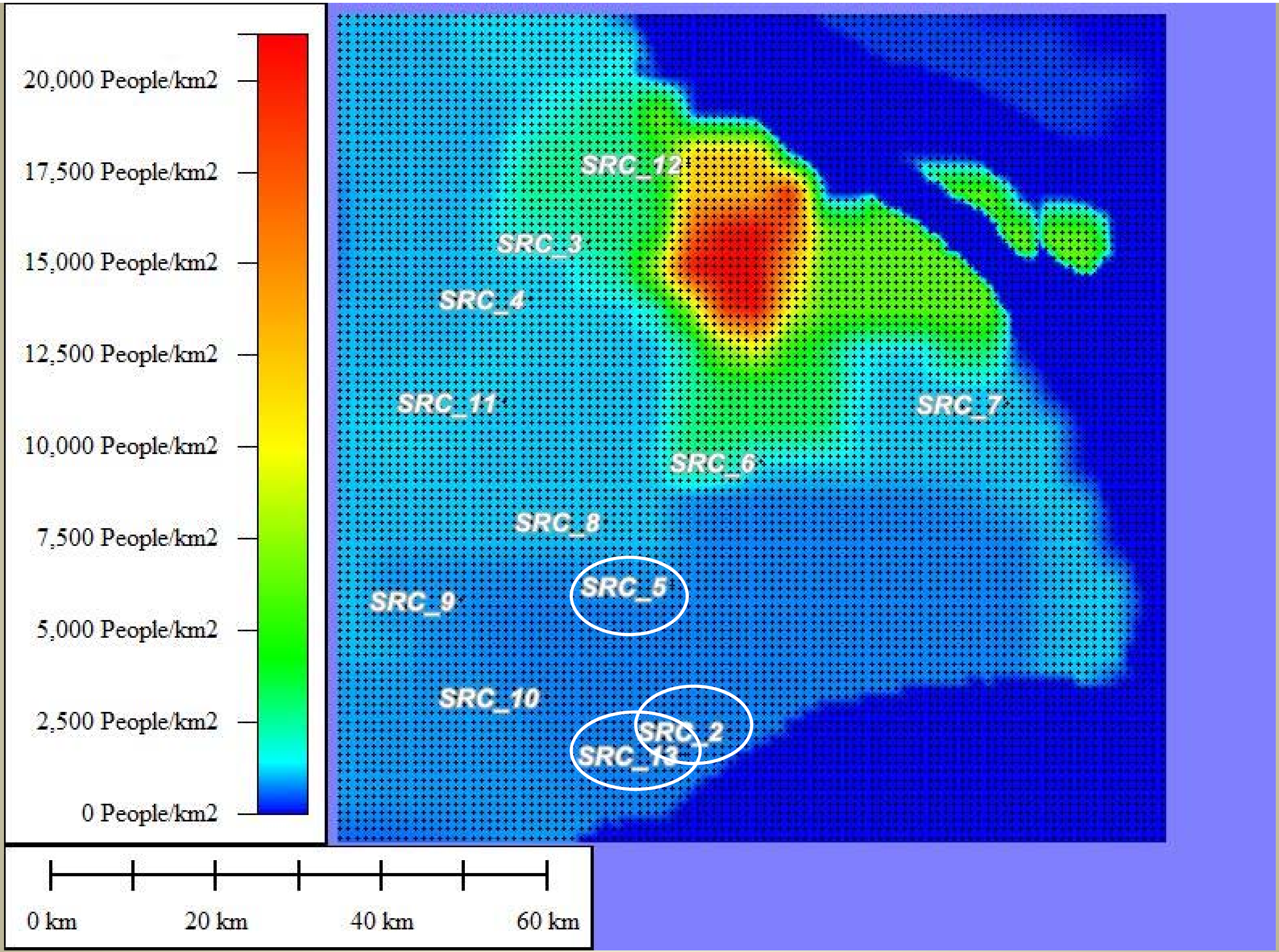
Total Cost of scrubbers for 3 power plants:
$1.5 B



"Common Sense" Scenario: reduce emissions of 3 closest stacks from the densest population area by ~80% (Wet Scrubbers for Sources 3, 6, and 12)

	Premature Mortality PM	Chronic Bronchitis CB	Respiratory Hospital Admission RHA	Cardiac Hospital Admission CHA	Restricted Acitivity Day RAD	Asthma Symptom Day ASD	Lower Respiratory Symptom Day LRSD	Total	
Totals	183	345	84	68	486	162,048	486	**163,700**	**Health Cases**
Percent	0.0012%	0.0022%	0.0005%	0.0004%	0.0031%	1.0%	0.0031%	**1.0%**	**Percent of Population**
Cost	40,313,890	10,136,506	87,176	70,831	4,114	523,539	486	**51,136,542**	**Cost Index**

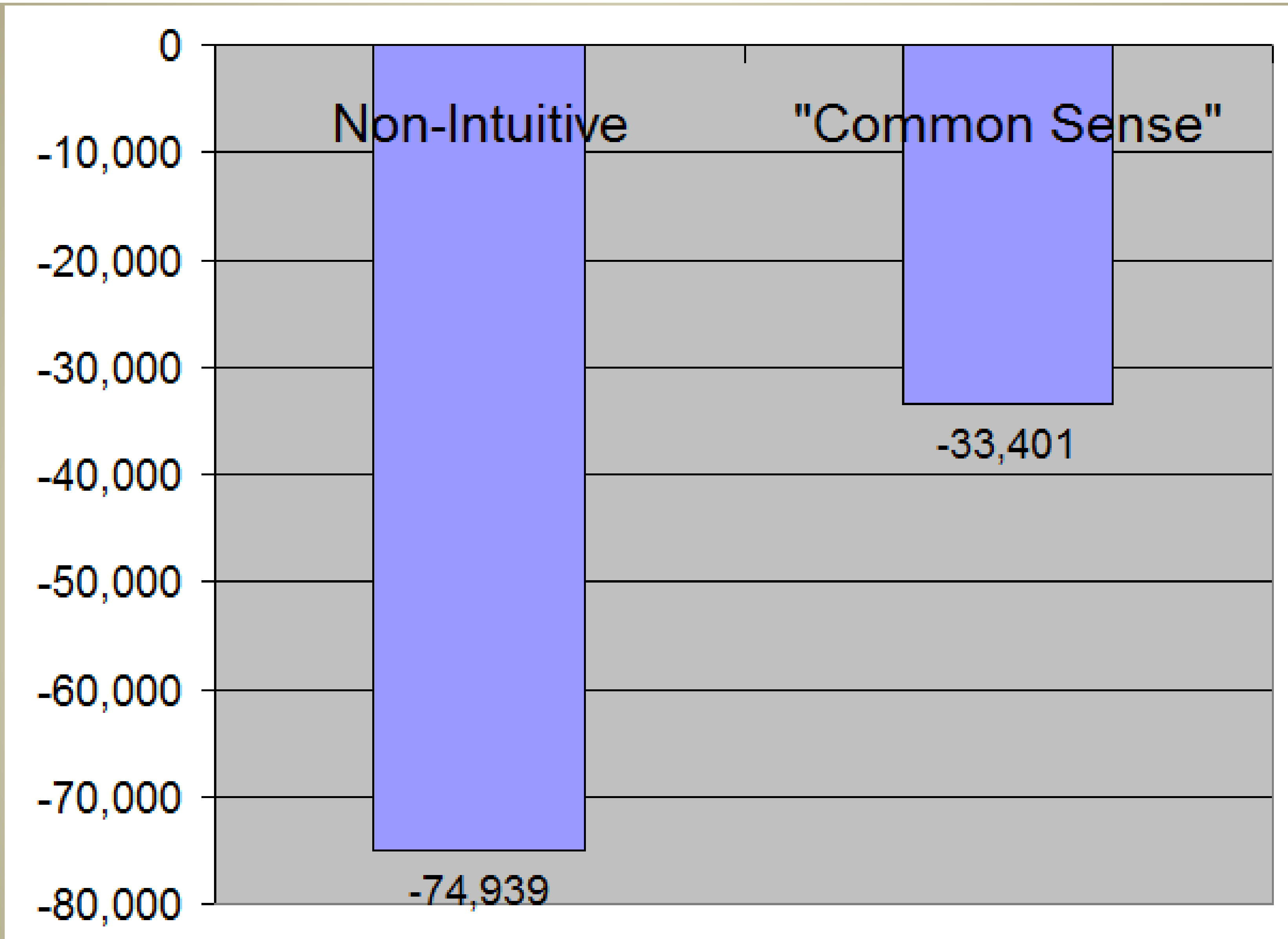
"Common Sense" Scenario: Health Cases and Costs due to 80% reduced Sulfate Concentrations for Sources 3, 6, and 12 (Health Cases reduced by 33,401, Cost Index reduced by 10,433,781)



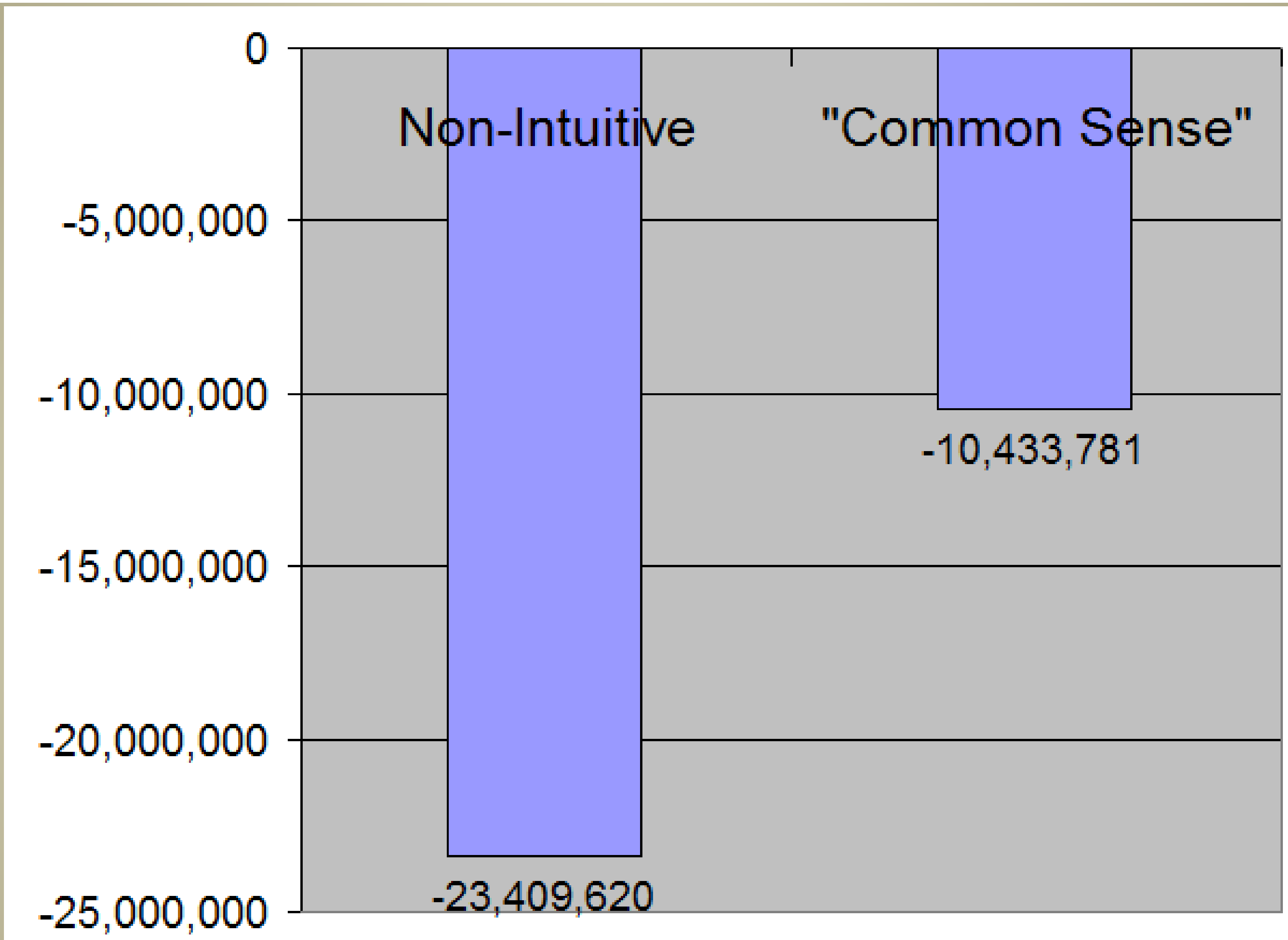
"Non-Intuitive" Scenario: reduce emissions of 3 distant stacks from the densest population area by ~80% (Wet Scrubbers for Sources 2, 5, and 13)

	Premature Mortality PM	Chronic Bronchitis CB	Respiratory Hospital Admission RHA	Cardiac Hospital Admission CHA	Restricted Acitivity Day RAD	Asthma Symptom Day ASD	Lower Respiratory Symptom Day LRSD	Total	
Totals	137	257	62	51	363	120,928	363	**122,161**	**Health Cases**
Percent	0.0009%	0.0016%	0.0004%	0.0003%	0.0023%	0.8%	0.0023%	**0.8%**	**Percent of Population**
Cost	30,084,287	7,564,379	65,055	52,857	3,070	390,691	363	**38,160,703**	**Cost Index**

"Non-Inuitive" Scenario:
Health Cases and Costs
due to 80% reduced Sulfate Concentrations
for Sources 2, 5, and 13
(Health Cases reduced by 74,939,
Cost Index reduced by 23,409,620)



Reduction in Total Health Cases for both Scenarios



Reduction in Relative Cost Index for both Scenarios

Prototype Demonstration

Conclusions

- Our prototype illustrates the advantages of using pre-allocated budgets to maximize air pollution benefits, instead of the traditional "air quality/emission standards" approach
- Objectivity vs. subjectivity
- Particularly useful for emerging countries, but in theory applicable everywhere
- Our goal is to continue the development of a general prototype, designed to facilitate introduction of site-specific data and cost-benefit functions
- Main objective: to find a region of interest for a first practical application using real data in collaboration with local agencies and scientific groups

Thank You!

zannetti@envirocomp.com