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Introduction to a Comprehensive Air Modeling/Optimization System (CAMOS)

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Introduction

Historically, air quality studies aiming at the solution of practical problems have focused on two main goals: 1) the improvement of air quality in areas contaminated by air pollution, and 2) the protection of regions with good air quality from possible future deterioration due to urban and industrial development. For example, since the passage of the Clean Air Act of 1970[1] the first goal was achieved in the US by establishing ambient air quality standards, i.e., levels of air pollution that should not be exceeded (and if they were, proper actions were implemented to achieve compliance with the standards). Also in the US, the second goal was achieved since 1977 with the establishment of the Prevention of Significant Deterioration[2], in order to protect and preserve existing good levels of air quality beyond the levels established by the air quality standards, especially in areas of special national or regional natural, recreational, scenic, or historic value.

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[1] http://www.epa.gov/regulations/laws/caa.html

[2] http://www.epa.gov/NSR/psd.html

In the US, and in many other countries that established environmental laws and regulations, substantial and measurable air quality improvements were achieved in the last decades. These improvements have had positive consequences, for example on human health.[3] These improvements were achieved through expenditures that covered the costs of study, design, implementation, and enforcement of regulations, and the costs carried by businesses and industries to comply.[4] It is reasonable today to ask ourselves several cost-benefit questions such as: 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?

The last question is probably the most important one. Instead of arguing what could have been done better in the past, when computers were not as powerful and user-friendly as today, we should focus on what can be done today with the current technology. The fact of the matter is that nowhere in the world have advanced computer simulation/optimization techniques been used 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) and enforcement, often partial and selective. Yet, when facing the enormous costs of environmental protection and air pollution control, it is reasonable to recognize that 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 which have recently shown a rapid industrialization, unfortunately associated with a distressing deterioration of air quality, especially in major cities. We all expect countries like China eventually to follow the historical pattern of the West (e.g., Europe and North America), which, after major industrial developments, was then able, in the last half-century, to develop environmental protection regulations and make major investments in remediation, with positive results that can be measured and verified in most (but certainly not all) regions. But one must wonder whether or not this historical path is 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.

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[3] According to a 1997 EPA Report to Congress, 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. http://www.epa.gov/oar/caa/40th_highlights.html

[4] For example, 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

The Example of China

Among the developing countries, China certainly occupies a special place for its size and the rapidity of its recent industrial and urban growth. China is experiencing high levels[5] of urban and industrial air pollution in many areas of its territory, especially in its highly populated coastal regions where air pollution adverse effects are very strong. China's air pollution problems are not much different from those experienced in Europe and North America in the 20th century. History teaches us that, eventually, with time, increase of GNP,[6] 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.

In spite of its air quality problems, which inevitably will get worse before getting better, China is in a unique historic position and can take full advantage of previous experiences in the Western world, including successes and mistakes, good investments and wasteful ones. More importantly, today we have advanced computer simulation tools - Air Quality Models - that have been well tested and calibrated.[7] 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.

Without a correct and expert application of these computer simulation tools, future decision making in China 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 would assure 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 to the population and the environment in general. These problems are extremely complex and non-linear. Only a set of well tested computerized tools can identify and provide optimal solutions, such as the actual implementation of urban and industrial planning and emission reductions strategies producing the maximum health and environmental benefits with fixed, pre-defined costs (or the minimum costs for fixed, pre-defined benefits).

These considerations, of course, can be extended to other developing countries and even to Western countries that still face today major air quality challenges, especially in cities due to emissions from motor vehicles.

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[5] http://www.guardian.co.uk/environment/2012/mar/16/air-pollution-biggest-threat-china
http://factsanddetails.com/china.php?itemid=392&catid=10&subcatid=66
http://www.reuters.com/article/2012/02/16/us-china-pollution-costs-idUSTRE81F09M20120216
http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt196.pdf
http://en.wikipedia.org/wiki/Pollution_in_China
http://www.chinadialogue.net/article/show/single/en/4775
http://blogs.wsj.com/chinarealtime/2013/01/30/chinas-air-pollution-problem-whose-responsibility/

[6] Gross National Product

[7] E.g., see http://www.epa.gov/scram001/ and http://www.acd.ucar.edu/wrf-chem/

The Challenge of Non-Linearity

Early air pollution studies focused on inert (or semi-inert) pollutants, such as sulfur dioxide, carbon monoxide, Lead, and others. Whenever these pollutants were found to exceed public health standards, one possible solution was relatively simple: to decrease emissions appropriately in order to decrease ambient concentrations. Emission decrease was linear (or quasi-linear) and therefore, if emissions were decreased by, say, 30%, one could expect a similar decrease in percentage in ambient concentrations. Extremely simple "rollback" models[8] were used for this purpose.

The problems caused by semi-inert pollutants are still important, but today the real air pollution challenge is typically found with pollutants like ground level (tropospheric) ozone[9] (O_3) and fine particles[10] ($PM_{2.5}$).

Ozone

High ozone concentrations in urban areas are a clear indication of the presence of photochemical smog,[11] which is a mixture of many substances and biological irritants chemically generated in the atmosphere and not directly emitted by sources. In fact, there are no direct emissions of ozone in the atmosphere. Ozone is generated by a series of chemical and photochemical reactions of VOCs,[12] NO_x[13] and solar radiation. These reactions are highly non-linear. In other words, 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[14] 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.

Clearly, advanced and well calibrated models are indispensable in identifying the most cost-effective emission reduction strategies to improve photochemical smog in large urban areas.

$PM_{2.5}$[15]

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[8] http://www.envplan.com/abstract.cgi?id=a060215
http://www.tandfonline.com/doi/abs/10.1080/00022470.1975.10470175#preview
http://www.otdmug.org/media/3886/chapter13.pdf
http://www.aqbook.org/read/?page=249
http://www.clarkcountynv.gov/Depts/daqem/Documents/Planning/SIP/PM10/App_K%E2%80%93Rollback_Methodology.pdf

[9] http://www.epa.gov/air/ozonepollution/

[10] http://www.epa.gov/airquality/particlepollution/designations/basicinfo.htm

[11] http://mtweb.mtsu.edu/nchong/Smog-Atm1.htm
http://dwb4.unl.edu/Chem/CHEM869J/CHEM869JLinks/royal.okanagan.bc.ca/mpidwirn/atmosphereandclimate/smog.html

[12] http://toxics.usgs.gov/definitions/vocs.html

[13] http://www.epa.gov/air/nitrogenoxides/

[14] http://dnr.wi.gov/air/pdf/attaindemoappE_voc_nox_ratio.pdf

[15] Incidentally, recent (January 2013) air pollution episodes in Beijing, China, have been characterized by very unhealthy ambient concentrations of $PM_{2.5}$ of 900 $\mu g/m^3$. See:

$PM_{2.5}$ indicates fine particles with effective diameter less than 2.5 micron. These particles are the most dangerous in causing adverse human health effects.[16] Also, these particles are the most efficient in impairing atmospheric visibility[17] by creating urban and regional haze. A large fraction of $PM_{2.5}$ is made of secondary particles, such as sulfates $SO_{4=}$ (generated from gaseous SO_2 emissions), nitrates NO_{3-} (generated from gaseous NO_x emissions) and organic particles (generated from gaseous VOC emissions). The gas-to-particle chemical reactions in the atmosphere are complex and non-linear and, therefore, as for ozone, sophisticated air pollution models are needed to simulate the effects of emission reduction strategies and identify the most cost-effective ones.

Conceptual Design

We envision the development of a series of interacting software modules that the user can access through a user-friendly GUI[18] 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 (under construction).

A user will start an interactive session with CAMOS and be presented with a window similar to the one illustrated in Figure 1 (main page).

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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).

[16] http://www.airnow.gov/index.cfm?action=particle_health.index

[17] http://www.epa.gov/airtrends/aqtrnd04/pmreport03/pmunderstand_2405.pdf

[18] Graphical User Interface

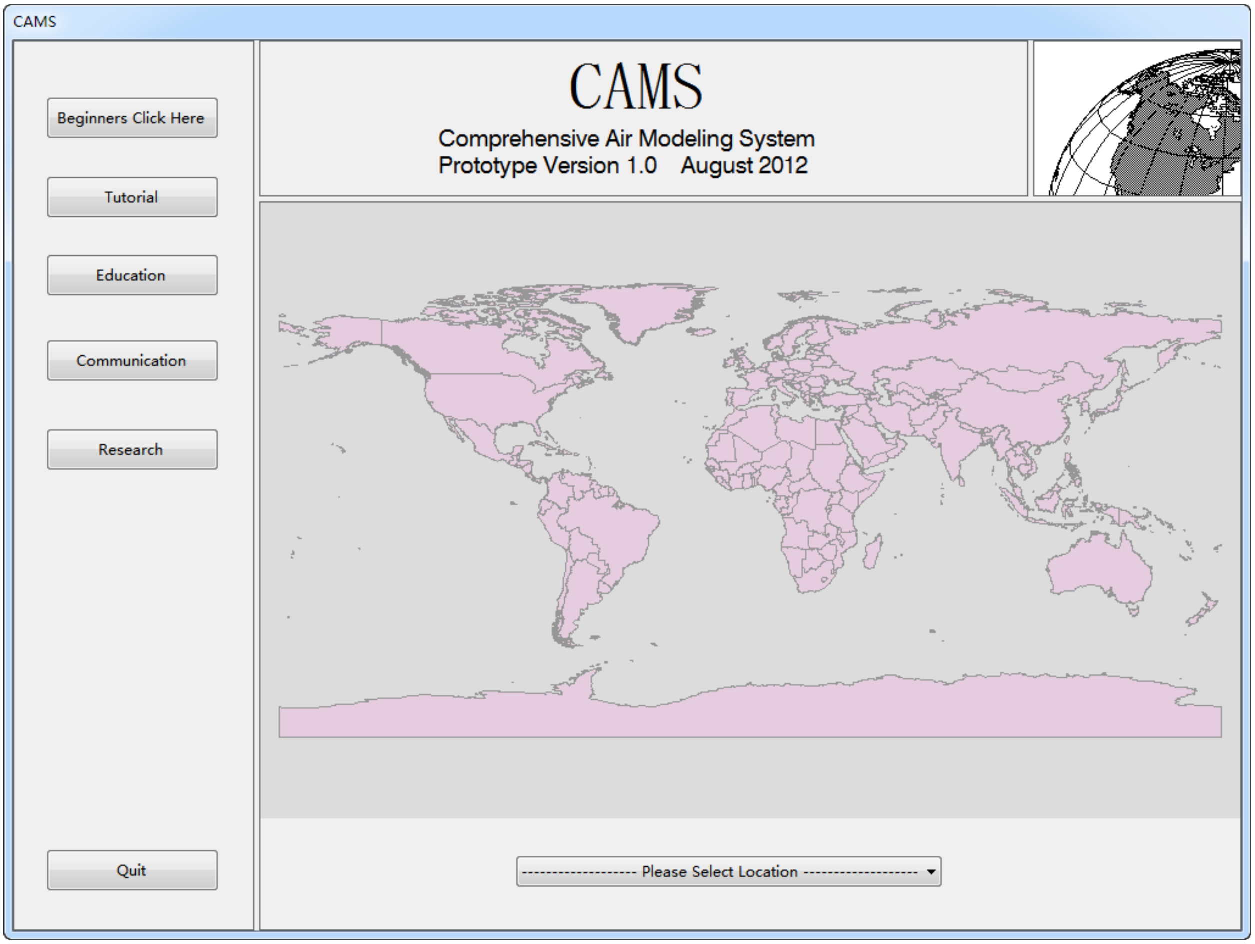

Figure 1 – CAMOS main page.

Through this window, the user may access several sections with tutorials, education modules, research sites, databases, and others. But the main use of CAMOS requires first a selection of a region by clicking on a world map or selecting through a list.

Once a region is selected, for example the metropolitan area of Shanghai, China, the user has access to a set of programs, models, and databases for that region, as illustrated in the left column of Figure 2. There will be at least one "baseline" scenario for each region. For example, for the Shanghai region we may have a baseline scenario referring to the year 2010 and containing a set of emission and meteorological data that allow to run a model (e.g., CALPUFF[19] or WRF-Chem[20]) and simulate ambient concentrations of pollutants of concern throughout 2010. We also assume that the baseline scenario has been successfully compared with available measurements in the region and, therefore, the baseline modeling is reasonably accurate.

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[19] http://www.epa.gov/ttn/scram/dispersion_prefrec.htm#calpuff

[20] http://www.acd.ucar.edu/wrf-chem/

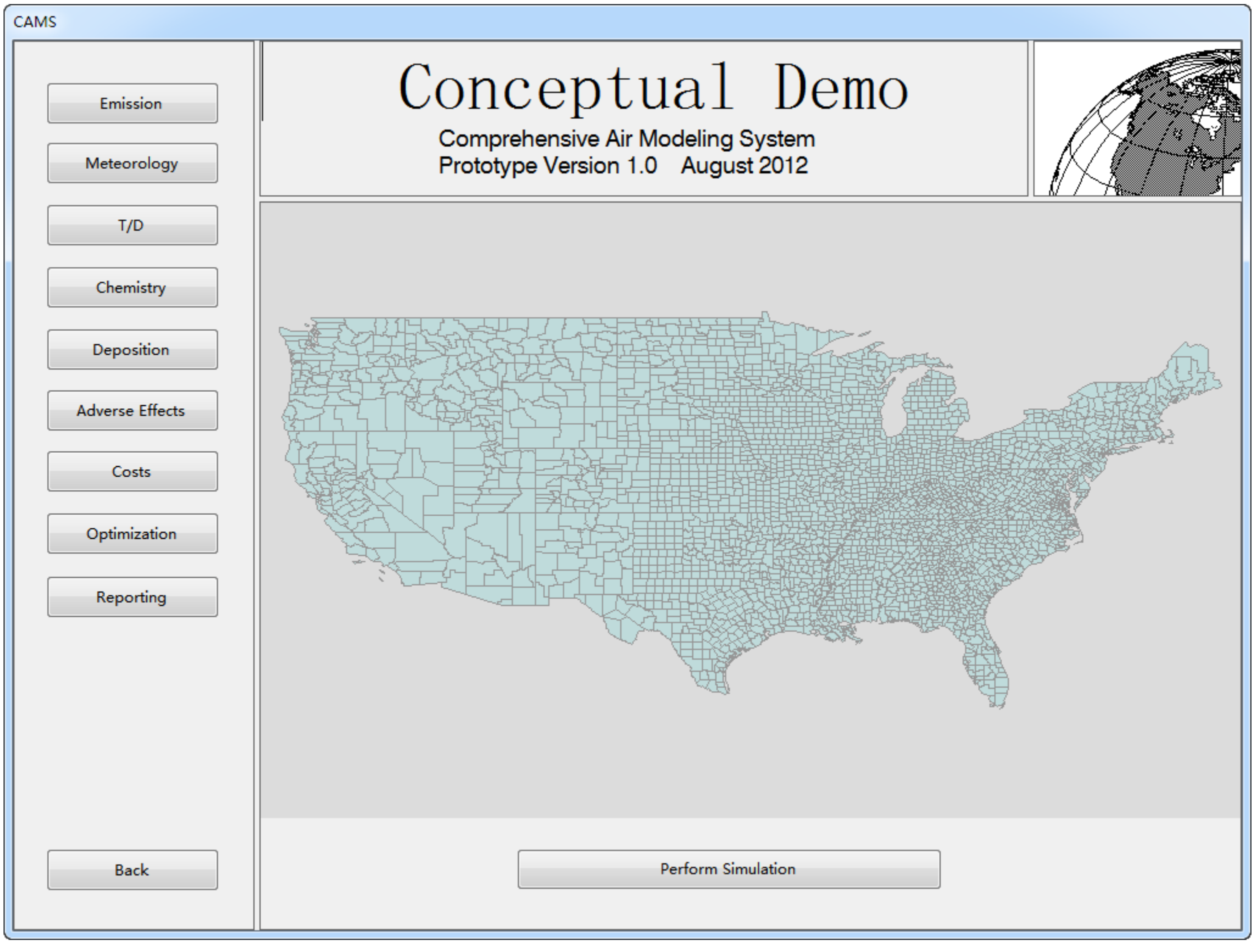
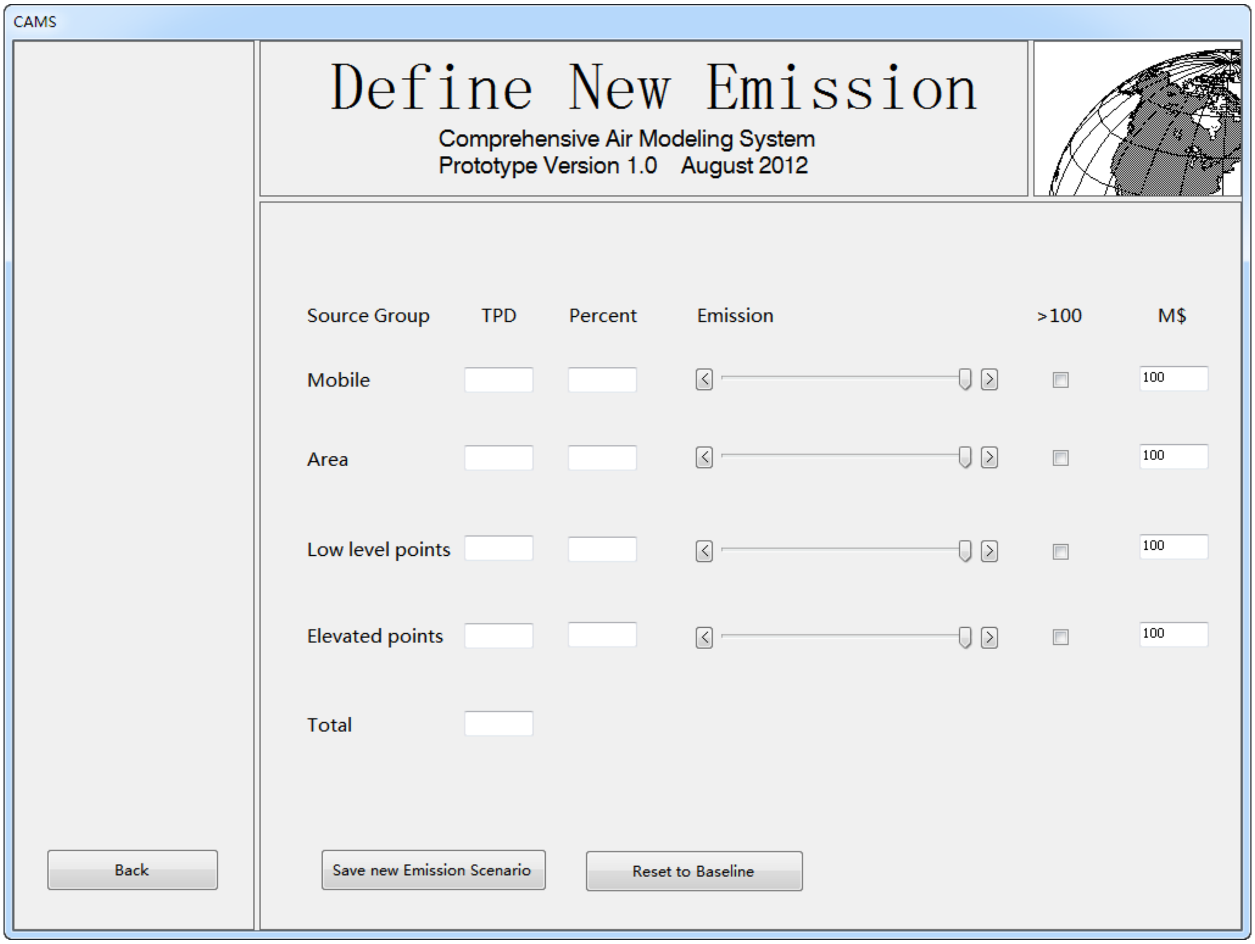


Figure 2 – Selection of a region of interest.

Once a baseline scenario is available, the user can start using the main simulation/optimization features of CAMOS by preparing emission reduction scenarios using the interactive window illustrated in Figure 3. For all the main emission sources and source groups, the user can specify a percentage reduction rate. Every reduction triggers an automatic calculation of the associated costs using a set a pre-defined cost functions for that region and that source. Once all reductions are inputted by the user, the new scenario can be saved and CAMOS automatically creates a new emission files for re-running the models and obtaining a new set of concentrations that can be compared with those of the baseline scenario.



Define New Emission

Comprehensive Air Modeling System
Prototype Version 1.0 August 2012

Source Group	TPD	Percent	Emission	>100	M$
Mobile				☐	100
Area				☐	100
Low level points				☐	100
Elevated points				☐	100
Total					

Figure 3 – Example of interactive window to create new emission scenario with automatic calculation of associated costs.

Therefore, in each grid point [i,j] the "improvement" in concentration $\Delta C_{i,j}(t)$ can be computed as a function of time. These improvements can be more of less important depending upon other variables, such as the population density in [i,j], the proximity to "sensitive" receptors, such as hospitals and schools, and other factors. CAMOS will then apply "benefit" functions to calculate the total benefits expected from the implementation of the new emission scenario. These benefit functions will be similar to those used in the literature, for example by the US EPA which calculated[21] the effects of regulations in preventing premature deaths, chronic bronchitis, heart disease, asthma attacks, cardiovascular hospitalizations, lost I.Q. points in children, and child respiratory illnesses.

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[21] The Benefits and Costs of the Clean Air Act, 1970 to 1990. Prepared for U.S. Congress by U.S. Environmental Protection Agency, October 1997 (http://www.epa.gov/oar/sect812/1970-1990/contsetc.pdf).

In a typical session, the user will create a new emission scenario, re-run the models with the new emission data, and obtain a detailed summary of costs versus benefits. CAMOS will include reporting utilities to summarize and visualize the results. In its ultimate version, CAMOS will include optimization and decision-support utilities to assist and guide the user toward the identification of the most cost-effective emission reduction strategies, instead of just letting the user experiment with new emission scenarios in a trial and error fashion.

The conceptual design of CAMOS will include the following main computational modules:

1. Emission module, to assist the user in preparing emission inventories and baseline emission databases
2. Meteorological module, including models such as CALMET[22], MM5[23], WRF[24]
3. Transport and diffusion module, including models such as CALPUFF[25]
4. Chemical reactions module, including models such as CAMx[26] and WRF-CHEM[27]
5. Dry and wet deposition module
6. Adverse effects module, i.e., a set of "adverse effects" functions that quantify in numerical terms the different (non-linear) adverse health/environmental effects expected to be caused by the simulated concentrations
7. Emission reduction cost module, i.e., set of (non–linear) cost functions that can be applied to each group of sources in a region to calculate the expected costs of any emission reduction strategy
8. Optimization module, i.e., an optimization/decision support software capable of guiding the user and suggesting the most cost-effective emission reduction strategies under different numerical constraints. (At least initially, this complex module can be bypassed by allowing the user to define different emission reduction strategies in a simple trial/modify mode)
9. Visualization and GIS module, i.e., GIS-based visualization tools to assist the user in the application of the different modules
10. Reporting module, to create automating reporting summaries for each user session

In addition, a GUI needs to be developed to allow the user to perform simulations and tests in a user-friendly manner. In fact, in its final configuration, we envision even a non-technical user capable of sitting in front of a computer screen and able, with little technical guidance, to run the CAMOS software, test emission reduction scenarios, calculate their costs, and run the modules to calculate the health/environmental benefits associated to each scenario.

Demonstration Prototype

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[22] http://www.epa.gov/ttn/scram/dispersion_prefrec.htm#calpuff

[23] http://www.mmm.ucar.edu/mm5/

[24] http://www.wrf-model.org/index.php

[25] http://www.epa.gov/ttn/scram/dispersion_prefrec.htm#calpuff

[26] http://www.camx.com/home.aspx

[27] http://www.acd.ucar.edu/wrf-chem/

We have developed a demonstration prototype that presents some of the key featured discussed above.

Partnership

Our goal is to develop CAMOS with a large number of regions incorporated into the system and ready to be investigated. To this end, we are searching for partners. There are more than a hundred reputable scientific groups in the world who have already developed, applied and validated advanced air pollution modeling tools in different regions of the world. We encourage these groups to consider partnership with us so that their databases and models can be included as baselines in CAMOS. The inclusion will allow our partners to benefit from the capabilities of the entire system and be able to use the system interactively for studies and presentations.

We believe that there are very high potential benefits in expanding the use of CAMOS to several regions on the world. The system will be a powerful tool for presentation to non-technical people, decision-makers, politicians, and the media.

Historically, in Europe and North America, improvements in air quality were achieved with “common sense” measures focusing on very large investments and general actions, such as the mandatory use of catalytic converters in new cars and reduction of emissions from stacks via regulations mandating the installation of air pollution abatement equipment. These measures were implemented with little or no optimization efforts. But countries today, especially emerging countries, have the unique opportunity to maximize positive results and make full use of today’s best available science and high computational resources.

It is important to underline that CAMOS has been designed not just to work for a specific city or region. The modules and the entire system have been designed with complete flexibility, so that their application to other regions will be straightforward.

Expected Results

If we succeed in having decision makers interested in objective strategic planning, we will be able to demonstrate how even our early prototypes can achieve higher benefits from different fixed-cost emission reduction strategies, and the potential power of the entire design. Decision makers will then fully realize that common sense and individual, subjective decision can be extremely inefficient and only through numerical optimization, efficient and objective decisions can be achieved.

Planners are often accused (and sometimes with good reason) to plan in their favor and to design and approve plans that benefit special groups and entities. By following the guidance of an objective computer system such as CAMOS, planners can show and document their actions and preempt accusations. This process can add a substantial level of integrity and transparency to governments’ and industries' decisions and choices. Decisions and plans are supported by data and documents that can be easily checked and reviewed by controllers.

We expect that the results of our modeling/optimization system will be sometimes surprising. For example, any calculation of benefits will be necessarily related to the density of population and, therefore, optimization efforts will tend to accept higher levels of air pollution in sparsely populated areas and maximize the need for improvements in densely populated areas. Similarly, a well designed cost-benefit system, able to calculate population exposure as a function a different lifestyles, may identify indoor air pollution as a greater threat than ambient air pollution for a large number of people who spend most of their time indoor (home, office). Again, we cannot anticipate the results, but we point out that results may well be unexpected and force decision makers to focus their efforts toward unanticipated solutions that happen to maximize benefits in a way not seen before.

Another example is diesel emissions. In California, diesel particulate matter has been identified[28] as the source of a very large fraction of the total cancer risk caused by toxic air pollutants. A study[29] by the California Air Resources Board also quantifies the very high role of particle diesel emissions in causing excess cancers in California. Therefore, it should not be a surprise if future cost-benefit optimizations performed with CAMOS would show the need of giving the highest priority to the reduction of diesel emissions in many regions.

Additional Developments

The CAMOS prototype described in the previous sections could be improved with additional simulation modules (e.g., to simulate urban ozone and toxic chemicals[30] such as benzene), and more complex cost/benefit functions. Also, advanced optimization modules could be included to provide a real Decision Support (DS) system to the user. Many improvements are expected to be added by interacting with decision makers and understanding their needs.

Our strategy is initially focused on academic goals. We will focus on the science and design of the project, to assure that the approach is based on modules that are scientifically valid and supported by the scientific literature. Later, when an adequate demonstration prototype becomes available, we plan to make an effort to find the support we need for the development of a complete system.

Eventually, the system could even be expanded to cover multiple environmental issues, not just air pollution.

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[28] See for example a study in the San Francisco Bay Area indicating that that diesel particulate matter accounts for over 80% of the cancer risk weighted toxic air contaminant emissions and that on-road and off-road mobile sources are responsible for the majority of cancer risk from air toxics. http://www.baaqmd.gov/Divisions/Planning-and-Research/CARE-Program.aspx

[29] California Air Resources Board report of July, 2005, illustrating in the figure at p 43 the very high role of outdoor diesel particle emissions in causing excess cancers in California http://www.arb.ca.gov/research/apr/reports/l3041.pdf

[30] http://www.epa.gov/tri/trichemicals/

Advantages of the System

In its final configuration, we expect to provide a Decision Support system (CAMOS) for urban/industrial development. Decision makers will be provided with a tool that visualize and quantify the effects of possible future scenarios for air pollution control in different regions. The system will be able to guide decision makers and suggest the most cost-effective emission reduction strategies, e.g., those that most benefit the largest number of people, or those that benefit some particular areas or segments of the population.

Expected Challenges

Most of the modules of our proposed CAMOS system already exist and are available at no cost. Here are the critical and most challenging development tasks:

1. Collect a preliminary database of chemical emissions (industry, traffic, etc.) in a selected region.
2. Select the proper existing modules (CALPUFF[31] is probably the best choice for the initial demonstration prototype).
3. Develop a set of "adverse effects" functions that quantify in numerical terms the different (non-linear) adverse health/environmental effects expected to be caused by air pollution levels. Formulas exist in the literature, but the quantification of "damage" remains a difficult task.
4. Develop a set of cost functions that can be applied to each group of sources to calculate the expected costs of any emission reduction strategy. Information exists in the literature, but there are large uncertainties.
5. Develop an optimization/decision support module capable of guiding the user and suggesting the most cost-effective emission reduction strategies under different numerical constraints. This is probably the most difficult task, even though methods and software are available.[32] At least initially, this complex module can be bypassed by allowing the user to define different emission reduction strategies in a simple trial/modify mode.
6. Create a user-friendly GUI capable to run the different modules and visualize the results

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[31] http://www.epa.gov/ttn/scram/dispersion_prefrec.htm#calpuff

[32] For example, there is software using Monte Carlo numerical methods to perform optimization and decision support; see: http://www.oracle.com/us/products/applications/crystalball/index.html