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A SCENARIO-BASED MODELING SYSTEM TO PREDICT THE AIR QUALITY IMPACT FROM FUTURE GROWTH

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ABSTRACT

This study presents the development and application of a scenario-based modeling system composed of a series of multiple modules within a GIS (Geographic Information System) framework to predict the air quality impact of *Alternative Futures* projected in a study area located in south western California. In this context, four future land use scenarios were developed each having two-population variants. Through a coupled system of transportation, meteorology/air quality, and emissions modeling, a spatially and temporally resolved emissions inventory reflecting future land use scenarios was calculated on a daily basis for an ozone (O_3) episode during July 2003. The Comprehensive Air Quality Model with extensions (CAMx) was used to estimate the photochemical processes in the system. Simulation results indicated varying impacts between the scenarios and predicted an increase in O_3 for all future development patterns.

Key Words: Urban Growth, Land Use Scenarios, Air Quality Modeling, Biogenic Emissions, Emissions Modeling.

1. Introduction

Air pollution is often associated with urbanization and industrialization. Starting from the early 20th century, a series of regulations targeted the reduction of air pollutant emissions from industrial sources; however, urbanization still remains an issue on both local and regional scales. The structure and design of urban developments can have significant adverse effects on pollutant emissions as well as other ecological factors (Southerland, 2004; Kepner et al., 2004). Diverse and poorly planned urban development (i.e., urban sprawl) can force higher rates of motor vehicle use and in return increase levels of pollutant emissions. Increased flood frequencies and habitat reduction of endangered species are also among the risks of such land cover changes (Kepner et al., 2004). Given the diversity and complexity of all these issues that adversely affect environment and air quality, there is a need to develop advanced tools which can predict the impact of future urban growth on all scales and recommend optimum approaches for achieving more sustainable environments. One effective method of assessing the future impact of urban growth is known as *Alternative Futures*, which is based on scenario analysis. Scenario techniques in land use planning have been around since the late 40's and been tested in many different applications to help the authorities in decision making (Schwartz, 1996; Steinitz, 1990; Shearer et al., 2004). In this study we introduce the development of an advanced interactive scenario-based land use and atmospheric chemistry modeling system coupled with a GIS (Geographical Information System) framework. The modeling system is designed to be modular and includes land use/land cover information, transportation, meteorological, emissions, and photochemical modeling components. The methods and modularity of the developed system allow its application to a broad region of interest. This paper describes the development and application of the modeling system to the rapidly developing area in south western California.

2. LAND USE SCENARIOS

To investigate the impact of possible land use change and urbanization, a set of alternative future patterns of land use were developed concerning the northern San Diego area and parts of Riverside and Orange Counties, California (Shearer et al., 2004). The study area for this purpose was defined as a rectangle of 73 miles east-west and 68 miles north-south. As discussed in Shearer et al. (2004), the set of alternative future land use scenarios or the *Alternative Futures* were based on a large spectrum of critical uncertainties representing the possible futures which are both difficult to predict and likely to have significant impact on social, economic, political, technological, and environmental trends. Issues were identified by looking at the critical uncertainties in the study area and addressed topics such as water, energy and possible changes in social and environmental regulations. To address these questions, four land use scenarios were developed each having two variants: a 500k population increase and a 1,000k population increase. The existing land use and land cover patterns were compiled using a Landsat Enhanced Thematic Mapper (ETM) image dated in November 18, 2000 and available information obtained from different sources. Land use maps for the future growth patterns including the existing land use are shown in Figure 1 (from Shearer et al., 2004). In all of the *Alternative Futures* the existing development (built) was left intact (Shearer et al., 2004).

The *Coastal Future* is built upon a scenario that encourages the conservation of future resources such as water and energy. As a result, high-density urban residential development is concentrated west of Interstate Highway 15 (I-15) close to the coast and the amount of low-density housing in more rural locations is reduced. Eighty eight percent of the new residential areas are located in San Diego County and ten and two percent in Riverside and Orange Counties, respectively.

The *Northern Future* represents a development plan that supports low density housing concentrated in the northern portion of the study area. Hence, the new suburban and rural residential development is concentrated in western Riverside County (44%) with the remaining development distributed in San Diego (55%) and in Orange (1%) Counties. Overall, the majority of housing is placed in subdivisions that are relatively close to incorporated cities and their associated infrastructure.

The *Regional Low-Density Future* best emulates the urban sprawl pattern of development present in the Western U.S. In this future scenario, the entire urban development is spread throughout the study area with new housing being predominantly developed on large lots. The majority of new housing is located in rural and ex-urban areas within San Diego (69%), Riverside (30%) and Orange (1%) Counties.

The *Three-Centers Future* concentrates development and assists in the conservation of some habitat. Much of the future housing is located close to existing development near the cities of Temecula, Vista, and Ramona. This lessens the amount of rural development sprawled throughout the southeastern part of the study area but adds some more rural residential development in the north. Percent distribution of the houses to the counties in the study area is the same as in the Regional Low-Density Future.

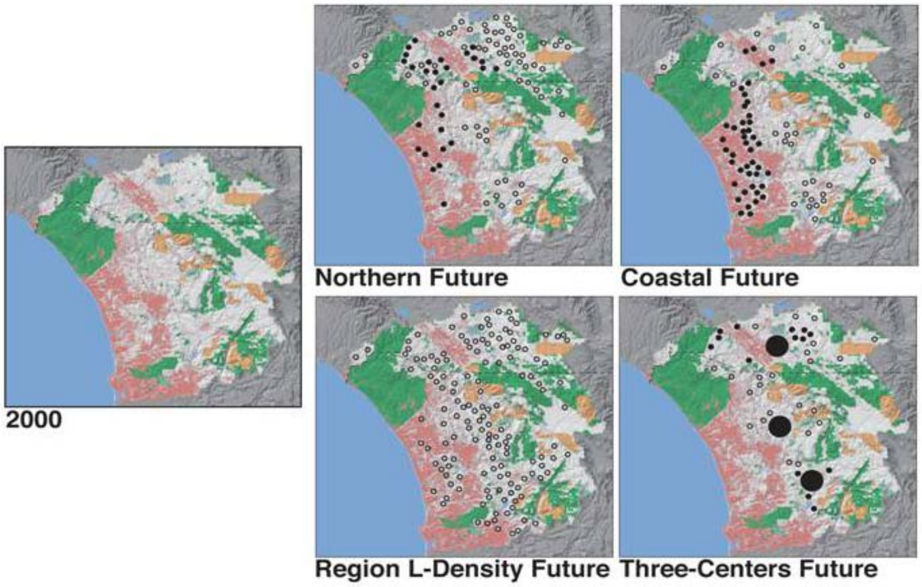

Figure 1. Land use map for the study area. (a) Existing land use (b) The *Coastal Future* (c) The *Northern Future* (d) The *Regional Low-Density Future* (e) The *Three-Centers Future.*

3. MODELING SYSTEM

In this section, an overview of the approach used to develop, test, and apply a modeling system to assess the impact of future scenarios on regional air quality is presented. A GIS based land cover and infrastructure system was coupled with pollutant emissions, meteorology, and air chemistry models. The modeling framework included a number of individual models involving future land use, emissions, air quality, and their subsequent linkages. The overall framework may be envisioned as a series of loosely coupled models with outputs and inputs shared among the models (Figure 2). The backbone of the framework is a GIS capable of operating at multiple spatial and temporal scales. Thus, each individual model encapsulated within the framework contains a spatial allocation, which can be mapped.

To create input scenarios for the emissions components, two models were constructed which describe the land use and transportation infrastructure in the region. The land use predictions, termed the development model, and the transportation model were linked to assist computation of commuting routes, which provided estimates of future vehicle miles traveled (VMT). Future emission assessments require knowledge on how an area may change and these rely on the development and transportation models for input. Air quality modeling requires inputs from all aspects of an emissions assessment. Any future alterations in population, technology, or laws will factor in as inputs into scenarios that have the potential to alter the outputs of any one model through cascading linkages. Thus, the modeling framework linkages were constructed to account for potential scenario-based changes.

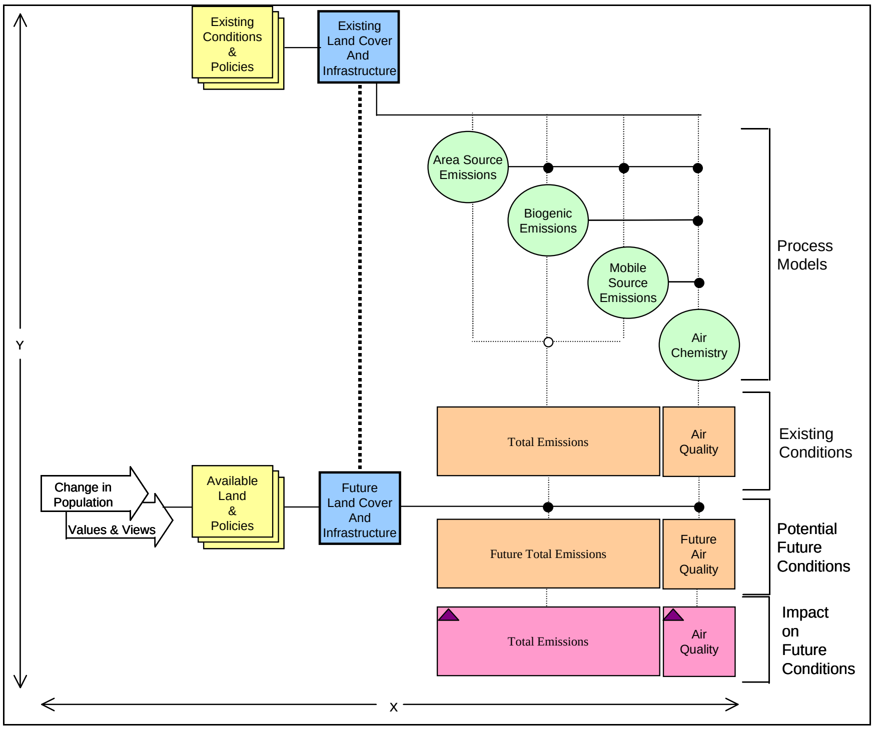

Figure 2. Framework for the assessment of air quality impacts using an *Alternative Futures* methodology. Process models, on the upper y-axis, reflect aspects of air pollution in the region of interest. The small black dots represent interaction points among process models. The region's social context, along the left portion of the x-axis, reflect varying future scenarios, including available land, policies, and the subsequent urban development and infrastructure. The relative future impact of these potential development changes is determined by integrating development changes with process models, as reflected by variations on "potential future conditions", on the lower y-axis. From the potential future conditions an assessment of how the development patterns change the air quality was done as reflected by the "impact on future conditions".

Brief descriptions of the three primary components of the modeling system (Transportation, Emissions, and Air Quality) are described below:

Transportation Modeling: Transportation models attempt to describe the flow of traffic between locations to allow for forecasting and analyzing future passenger and/or freight movement (Beimborn et al., 1996). The transportation model developed for this system accommodated all the basic conditions that are required

(Beimborn et al., 1996), with a minimal level of complexity. The primary intent of this modeling approach was to route present and future passenger cars in the study region from their home locations to their destinations along the quickest path. The model was structured in a GIS platform to coordinate all the spatial aspects and linkages of spatial information with the future land use data using Tiger line transportation files and the associated attribute information as a foundation for determining the VMT between home and work (USCB, 2002a). Based on the results of the development model, starting points were identified as new housing units defined in a 30x30 m^2 cell within a GIS layer. The ending locations were determined as thirteen major commuting points or work centers within the study area or as locations where commuters would exit the study area heading mainly north to Los Angeles or to northern Riverside County. Although substantially more work centers exist in the region, this assumption was based on the fact that many of these are clumped into the represented commercial-industrial centers. Homes were randomly assigned a path to a commercial-industrial work center as a percentage derived from U.S. Census county commuter information (USCB, 2002b).

Emissions Modeling: The emissions component of the model incorporated emissions models for biogenic, area-wide, and mobile sources. Emissions were computed for the five pollutants: NO_x, sulfur dioxide (SO_2), volatile organic carbon (VOCs), carbon monoxide (CO), and particulate matter (PM). Existing emissions estimates served as a base for estimating future emissions. The final product of the emissions modeling was a 5x5 km^2 gridded hourly day specific emissions inventory for the modeling episode of July 7 – 11, 2003.

Spatially and temporally variable biogenic emissions were estimated for the photochemical modeling domain. Estimated biogenic emission species consisted of biogenic volatile organic carbons (BVOC) such as isoprene, monoterpenes, and methylbutenol. The California Air Resources Board's (CARB) biogenic emissions model, BEIGIS, was used as the basis for the biogenic emissions component of the model. BEIGIS is a GIS based biogenic emissions model that is built upon biomass and emissions studies performed in Southern California (Horie et al., 1991; Benjamin et al., 1996). Default emission rates given in BEIGIS come mostly from Horie et al. (1991) and Benjamin et al. (1996, 1997).

Area-wide emissions of the future land uses were estimated based on the use of consumer products, residential natural gas consumption, dry cleaning, and residential and commercial lawn maintenance. These categories were determined according to the given details in the future scenarios. Methodologies used for area source emission estimates were based on the CARB's Emissions Inventory Procedure Manual (CARB, 1997). Total emission rates were allocated spatially and temporally for each land use scenario. In contrary to biogenic emissions estimates, area-wide emissions of the future scenarios were superimposed on the current emissions layer due to the fact that existing land use was preserved in the scenarios.

To estimate future on-road mobile source emissions, the GIS-based travel simulation algorithm described in the transportation model section was utilized in conjunction with EMFAC2002, the on-road emissions model specific to California (CARB, 2002). This model calculates emission factors and/or emission rates for the vehicle fleet in California as categorized in 13 vehicle classes and accounts for six criteria pollutant types. Total VMT served as the major input for EMFAC2002 as calculated by the transportation model.

Meteorological and Photochemical Modeling: In order to evaluate the impact of the future scenarios on the formation of secondary pollutants, the spatially and temporally resolved output from the emissions model was coupled with an air quality modeling system that can operate over multiple domains. This took place in two steps: meteorological and photochemical air quality modeling. As part of this study, simulations were performed for an episode from July 7 through July 11, 2003. During this period, the San Diego area experienced high levels of air pollution and so it provided an opportunity to investigate the possible highest impact of the future land use change on air quality.

A prognostic forecast model, the Fifth Generation Penn State/NCAR Mesoscale Model (MM5) (Grell et al., 1995), was used to generate all required field variables and parameters for the emissions model and the air quality model. MM5 is a well-known mesoscale, nonhydrostatic, terrain-following sigma coordinate model that is used in predictions of mesoscale and regional air circulation. MM5 provided the photochemical model with 3-dimensional field variables such as horizontal wind, temperature, pressure and other parameters, which are used by the photochemical model for the atmospheric transport and dispersion calculations. Temperature and ground level shortwave radiation variables used in biogenic emissions model were also predicted by MM5.

To address the formation of secondary species and transport/dispersion of emissions, the Comprehensive Air Quality Model with extensions (CAMx) was employed (Environ, 2003). CAMx is a photochemical Eulerian dispersion "one-atmosphere" modeling system with multi pollutants and scaling that can be applied to regional or local domains to predict all phases of air chemistry. The model requires a variety of input variables including meteorological fields, photochemical reaction rates, gridded and/or point emissions, surface characteristics, initial conditions (IC), and boundary conditions (BC). For all the simulations, IC and BC were set according to the U.S. EPA's standard profiles.

4. RESULTS AND DISCUSSION

4.1. Emissions

Total future emission estimates were generated on a daily basis for the same time period as the air quality model was run. The final product of the emissions modeling was a 5x5 km^2 gridded hourly emissions inventory of NO_x, SO_2, VOCs, CO, and PM. Within the study time period, the greatest change in emissions occurred on July 10 and was due to changes in biogenic emissions driven by the ambient temperatures. In terms of the other anthropogenic emission sources, it was assumed that the modeling period extended throughout the weekdays with the same activity rate and therefore no changes were predicted on a daily basis. Land use differences had the greatest influence on two categories: mobile and biogenic sources. Area wide emissions showed a linear dependence on population, and stationary/industrial sources were assumed unchanged in this study. Although the difference between the four scenarios was small in terms of the mobile source contribution, the *Northern*

Future generated the highest emissions and the *Three-Centers Future* generated the smallest values. This was attributed to the longer commuting paths and associated higher VMT rates for the *Northern Future*.

VOC emissions from biogenic sources, on the other hand, demonstrated completely different characteristics and have very distinct differences among the scenarios. This change was by virtue of the quantity and quality of the altered land in the future scenarios. In some of the scenarios, the amount of rural housing built on large lots that leads to higher emission rates (Benjamin et al., 1997) was larger than for the other scenarios and was the major factor for higher emission estimates. The *Regional Low-Density Future*, for example, had twice as much land allocated as new residential areas than the other scenarios and 80% of it was classified as rural. This, and the fact that most of the low emitting or non emitting land (e.g., barren, grassland, etc.) was converted into residential vegetation uses, led to the highest amount of biogenic VOC emissions, an increase of 44 tons from the base case. In contrast, the lowest biogenic emissions occurred in the *Three-Centers Future,* which has the smallest percentage of higher-emitting rural lots. Overall biogenic emissions were greater than or nearly the same as the total estimated anthropogenic VOCs. This highlights the importance and magnitude of biogenic emissions from urban areas.

4.2. CAMx Simulations

The air quality simulations using CAMx were performed for the period of July 7 through July 11, 2003 and covered an observed O_3 episode in the region. The first day of the simulations, July 7, was excluded from the analysis and was used as the model's spin-up time.

For all the simulations, the maximum predicted O_3 concentrations occurred on July 11. This situation was associated with low daytime wind speeds and relatively stagnant conditions. The location and time of the peak concentration over San Diego and Riverside Counties were approximately the same for all days. Table 1 presents the simulated peak O_3 concentrations for the base case and scenarios on a daily basis. It is seen from this table that the peak O_3 increases 10 ppb, on average, for the *Regional-Low Density Future* and ranges from 2 to 9 ppb for the other scenarios, suggesting that the most of the impact is local. These results show that both the regional and local impact is the least for the *Three-Centers Future,* which also had the smallest incremental changes in emissions.

The results shown in Table 1 indicate that while the base case is below the one-hour average federal standard for O_3 on July 9 and 11, all scenarios with 1,000k new residents are likely to exceed this standard. Unless the future growth plans include some mitigation measures, the area will be classified as non-attainment. Such measures could include newer and cleaner technologies in motor vehicles and the planting of selected plant species to reduce BVOCs (Benjamin and Winer 1998; Pun et al., 2002; Mendoza-Dominguez et al., 2000).

Table 1. One-hour average predicted peak O_3 concentrations (ppb) over the study area and San Diego County for the entire simulation period. *Max* O_3 column designates the predicted peak O_3 concentration and *Change* (ppb) column designates the difference with respect to the base case.

Simulations	July 8		July 9		July 10		July 11	
	Max O_3	Change	Max O_3	Change	Max O_3	Change	Max O_3	Change
Base Case	100		114		106		117	
Coastal Future (500k)	102	2	119	5	110	4	120	3
Coastal Future (1,000k)	105	5	123	9	115	9	124	7
Northern Future (500k)	103	3	119	5	111	5	121	4
Northern Future (1,000k)	105	5	122	8	114	8	124	7
Reg. Low-Density Future (500k)	104	4	121	7	113	7	124	7
Reg. Low-Density Future (1,000k)	108	8	126	12	118	12	128	11
Three-Centers Future (500k)	102	2	118	4	109	3	120	3
Three-Centers Future (1,000k)	103	3	121	7	112	6	122	5

6. SUMMARY AND CONCLUSIONS

In this paper we described the development and application of a scenario-based modeling system that couples a GIS based land cover and infrastructure system with pollutant emissions, meteorological and air chemistry models to predict the impact of growth on future emissions and air quality. Four land use and land cover scenarios with each having a 500k and 1,000k population increase were developed within a GIS system to depict the possible future growth and its consequences within the study area (Shearer et al., 2004). Subsequently, we linked this GIS system with transportation, emissions, meteorological and air quality models to predict air quality impacts for each scenario.

Emission estimates and air quality simulations were performed for an observed episode in the South Coast region and San Diego County from July 7 to 11, 2003. Estimates of future emissions were distinctly different for the four scenarios. Changes in BVOC emissions were comparable to the changes in the total anthropogenic VOC emissions. Overall the *Regional Low-Density Future* was seen to have the highest pollutant emissions and the greatest impact on air quality. On the other hand, the *Three-Centers Future* appeared to be the most beneficial alternative future in terms of air quality. For all cases, the increase in population was the main factor leading to the change on predicted pollutant levels.

As standards for air quality become more stringent, the need for predictive tools that can assess the impact from future growth and developments is critical. The modeling system and simulation results presented in this paper were aimed to answer the question of what and how *Alternative Futures* should be designed if we are to implement effective strategies to reduce future air quality impacts. Since the system is fully modular and capable of integrating new sub-systems, it can be modified to include additional features as desired and applied a variety of regions where future development and growth plans are needed.

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