

## **Appendix G.4**

### **Phase 2 HGB Mid Course Review**

### **Comparison of Observed and Modeled Isoprene Concentrations in Southeast Texas during the Texas Air Quality Study**

**Prepared by**

**Jihee Song, William Vizuete, Yosuke Kimura, and David T. Allen  
Center for Energy and Environmental Resources  
University of Texas**

**and**

**Harvey Jeffries  
Department of Environmental Sciences and Engineering  
University of North Carolina**

**Submitted to Atmospheric Environment, 2004**

# **Comparison of observed and modeled isoprene concentrations in southeast Texas during the Texas Air Quality Study**

Jihee Song, William Vizuete, Yosuke Kimura, and David T. Allen\*  
Center for Energy and Environmental Resources, University of Texas

Harvey Jeffries  
Department of Environmental Sciences and Engineering, University of North Carolina

## **ABSTRACT**

The Global Biosphere Emissions and Interactions System (GloBEIS) was used to predict biogenic isoprene emissions in the Houston-Galveston Area (HGA) in southeast Texas. The estimates were based on a land cover database with a spatial resolution of approximately one kilometer and emission factors taken from literature. A gridded photochemical model was then used to predict the spatial and temporal patterns of isoprene concentrations, based on the emission inventory. Predicted concentrations were compared to aircraft observations, and the sensitivity of model predictions to assumed patterns of surface temperature, cloud cover, and land cover were assessed. Predicted concentrations had an average gross error, compared to observations, of 30-80%, with a bias of approximately -10%. When the comparison of predicted and observed values included all observations the average gross error was 80%; when the comparison was limited to observed isoprene concentrations  $> 0.1$  ppb and  $> 0.2$  ppb, the average gross error was reduced to 50% and 30%, respectively. Sensitivity analyses indicate that differences between predicted and actual land covers are the largest source of potential uncertainties in biogenic emission estimation.

\*Author to whom correspondence should be addressed

Keywords: isoprene, biogenic volatile organic compounds, biogenic emissions, photochemical modeling

## INTRODUCTION

Biogenic volatile organic compounds (BVOCs), including isoprene ( $C_5H_8$ ), monoterpenes ( $C_{10}H_{16}$ ), and oxygenated compounds, are emitted in substantial quantities by vegetation (Guenther *et al.*, 2000, Wiedinmyer *et al.*, 2000; Helmig *et al.*, 1999; Kempf *et al.*, 1996; Guenther *et al.*, 1995; König *et al.*, 1995; Fehsenfeld *et al.*, 1992; Winer *et al.*, 1992). The United States Environmental Protection Agency (USEPA) has estimated that total emissions of biogenic VOC emissions in the United States are  $30 \text{ TgC yr}^{-1}$ , which is an amount greater than estimated anthropogenic VOC emissions. Emissions of isoprene, a highly reactive BVOC, accounted for 17-20  $\text{TgC yr}^{-1}$  of the total BVOC inventory (Guenther *et al.*, 2000).

In heavily forested regions of the eastern half of Texas, biogenic emissions of isoprene dominate the emission inventory for reactive hydrocarbons. On a typical summer day, biogenic emissions (primarily isoprene) can exceed 10,000 metric tons  $\text{day}^{-1}$  (approximately 10 gigagrams  $\text{day}^{-1}$ ) (Wiedinmyer *et al.*, 2001), summed over the eastern half of Texas. In contrast, total anthropogenic emissions of hydrocarbons, summed over the same area, is of order 2,000 metric tons  $\text{day}^{-1}$ . While biogenic emissions of hydrocarbons dominate the overall emission inventory in eastern Texas, the spatial distribution of emissions is heterogeneous. In heavily forested areas of eastern Texas, biogenic emissions overwhelm anthropogenic emissions. In highly urbanized areas, anthropogenic emissions are more significant. A number of transition zones exist, where both biogenic and anthropogenic emissions are significant fractions of the emission inventory and the relative roles of biogenic and anthropogenic emissions in ozone formation and other photochemical processes depends on meteorological conditions. Portions of southeast Texas provide examples of this type of transition zone, and in these transition regions, accurately characterizing the spatial distribution of biogenic emissions, over a large spatial domain, is an important element in developing air quality improvement plans.

Developing accurate estimates of the spatial distribution of biogenic emissions relies on accurate characterizations of land covers (leaf biomass densities by species), surface

temperatures and photosynthetically active radiation (PAR). Wiedinmyer *et al.* (2001) has reported on the development of a land use/land cover database for Texas at a spatial scale of 1 kilometer. This work will report on the use of that land cover database, together with a variety of estimates of temperatures and PAR, to estimate biogenic emissions during an August-September 2000 photochemical episode. The accuracy of the biogenic emission estimates will be assessed by comparing isoprene concentrations, observed in aircraft measurements, to isoprene concentrations predicted using the emission inventory coupled with a photochemical model. The sensitivity of predicted concentrations to assumed patterns of surface temperature, cloud cover, and land cover will be assessed.

## **METHODOLOGY**

### ***Biogenic emission inventory***

The Global Biogenic Emissions and Interactions System (GloBEIS) was used to develop the emission inventory (Yarwood *et al.*, 1999a, b). GloBEIS requires data on land use/land cover (LULC), temperature, leaf area index (LAI), drought index and photosynthetically active radiation (PAR) to estimate biogenic emissions. All the simulations reported in this work used the GloBEIS 3.1 model. The sources of LULC, temperature, PAR, LAI, drought index, and antecedent leaf temperature are described below.

The LULC input data required by GloBEIS were derived from a Texas vegetation database developed by Wiedinmyer *et al.* (2000, 2001). The data are available at a 1-km resolution for a domain encompassing most of Texas; The LULC database contains emission factor data for 156 different vegetation types, including 41 species (e.g., *Quercus alba*), 80 genera (e.g., *Quercus*), and 35 land cover types (e.g., Pecan Elm forest). Each classification is assigned a vegetation species, leaf biomass, and density distribution (Wiedinmyer *et al.*, 2001).

Hourly ambient surface temperatures were developed by spatially interpolating temperatures measured by National Weather Service (NWS) and other weather stations

throughout southeast Texas (Vizuete *et al.*, 2002). Estimates of PAR flux were based on calculations done by the University of Maryland and the National Oceanic and Atmospheric Administration (NOAA) for the Global Energy and Water Cycle Experiment (GEWEX) Continent Scale International Project (GCIP). NOAA uses a modified version of the GEWEX surface radiation budget (SRB) algorithm (version 1.1) to calculate radiation flux fields from Geostationary Operational Environmental Satellite (GOES-8) data (TCEQ, 2003).

Wind speed and humidity estimates were derived from simulations using the MM5 meteorological model. MM5 is the fifth generation NCAR/Penn State Mesoscale Model. Variable leaf area index (LAI) values are based on a standard 8-day average LAI product from the Moderate Resolution Imaging Spectroradiometer (MODIS). LAI is derived from the atmosphere corrected surface reflectance of two bands (648 and 858 nm) and a 1 km resolution land cover map of six major biomes, characterized by the horizontal and vertical dimensions, canopy height, leaf type, soil brightness and climate, produced from MODIS. LAI, the area of leaves per unit of ground area, is used to determine the amount of leaf biomass and/or model effects due to leaf age in GloBEIS 3.1.

Palmer drought index (PDI), which is an index of moisture deficiency or excess, is empirically derived from the monthly temperature and precipitation scenarios of 13 instances of extreme drought in western Kansas and central Iowa and by assigning an index value of -4 for these cases. Conversely, a +4 represents extremely moist conditions. From these values, categories of wet and dry conditions are defined. The average drought index for eastern Texas in August 2000 was -3.5, which indicates severe drought conditions ([http://www.cpc.ncep.noaa.gov/products/analysis\\_monitoring/regional\\_monitoring/palmer/2000/08-26-2000.gif](http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/regional_monitoring/palmer/2000/08-26-2000.gif)). GloBEIS 3.1 assumes that isoprene emissions are not directly influenced by drought for a PDI above -2 and that emissions decrease linearly to 10 percent of no-drought conditions for a PDI of -4.

In GloBEIS 3.1, isoprene emissions also depend on the average temperature during the past 24, 48, and 360 hours (Geron *et al.*, 2000, Sharkey *et al.*, 2000, and Petron *et al.*, 2001). The averaged temperatures during previous 24, 48, and 360 hours are calculated within GloBEIS 3.1.

Emissions are calculated as:

$$\gamma_T = \gamma_{T1} [1 + 0.04 (T_{18} - 301) + 0.02 (T_{48} - 301) + 0.14 (T_{360} - 301)]$$

Where  $\gamma_T$  is the activity factor accounting for the temperature of the past hour,  $T_{18,48,360}$  is the mean temperature (K) of the past 18, 48, and 360 hours, respectively (Environ, 2002).

### ***Predictions of isoprene concentrations***

Concentrations of isoprene, based on the emissions estimated using GloBEIS, were predicted using the Comprehensive Air Quality Model, with extensions (CAMx, [www.camx.com](http://www.camx.com)). This model is used by the State of Texas in developing air quality management plans; the State is using CAMx to describe a photochemical episode that occurred in southeast Texas from August 25, 2000 to September 1, 2000. This episode occurred during a large air quality field study and the performance of the model in predicting ozone concentrations has been evaluated using the extensive dataset available from the field program.

CAMx and similar eulerian photochemical grid models simulate emission, advection, dispersion, chemical transformation and physical removal of air pollutants in the framework of a 3-dimensional grid. The horizontal and vertical grid structure used in this work is shown in Figure 1. Wind field inputs were provided by the Texas Commission on Environmental Quality (TCEQ) using the MM5 meteorological model; emissions (other than biogenic emissions) were based on the emission inventories assembled by the State with some adjustments to the point source data based on ambient observations. Additional details of the model development, and an evaluation of model performance in predicting ozone concentrations, are available at the TCEQ web site: ([http://www.tnrcc.state.tx.us/air/aqp/airquality\\_photomod.html#section4](http://www.tnrcc.state.tx.us/air/aqp/airquality_photomod.html#section4)).

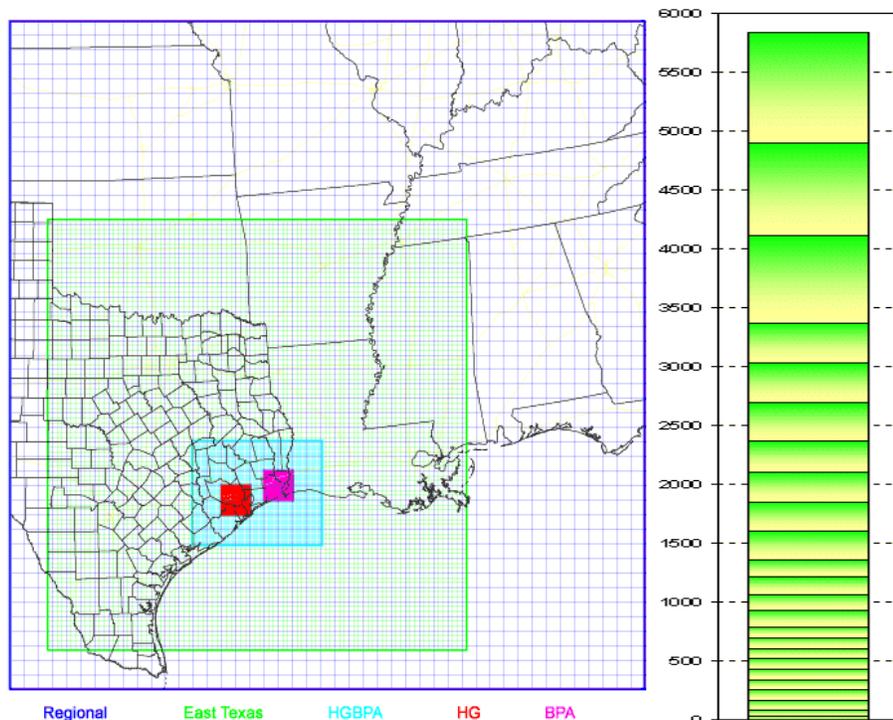


Figure 1. Air quality modeling domain: The domain's horizontal structure consists a coarse grid regional domain (36 km by 36 km resolution) and three nested fine grid subdomains; an East Texas subdomain (12 km by 12 km), Houston/Galveston-Beaumont/Port Arthur subdomain (4 km by 4 km), Houston/Galveston Bay subdomain (1 km by 1 km), and the Beaumont/Port Arthur subdomain (1 km by 1 km). The domain's vertical structure is given on the right hand side of the Figure. Each cell represents a modeling layer and the starting and ending heights of the cells are given in meters above ground level.

Isoprene is modeled as an explicit chemical species in the photochemical modeling, which employed Version IV of the Carbon Bond mechanism (CB-IV). Isoprene reactions with OH $\cdot$ , O $_3$  and NO $_3$  are included in the mechanism. The rate constants have been optimized based on chamber experiments (Carter *et al.*, 1996). The values used in the model are  $1.476 \times 10^5$  for the OH radical reaction,  $1.9 \times 10^{-2}$  for O $_3$  and  $996 \text{ ppm min}^{-1}$  for NO $_3$  all at 298 K.

### ***Measurements of isoprene concentrations***

During the Texas Air Quality Study (TexAQS, [www.utexas.edu/research/ceer/texaqs](http://www.utexas.edu/research/ceer/texaqs)), conducted in August and September, 2000, a variety of measurement platforms recorded isoprene concentrations. Both aircraft and ground measurement platforms were used; however,

since the focus of this work is on evaluating the spatial distribution of biogenic emissions, the primary source of isoprene concentration data that will be considered will be from aircraft platforms. A team from the National Oceanic and Atmospheric Administration aboard an Electra aircraft provided by the National Center for Atmospheric Research (NOAA/NCAR Electra) and a team from Brookhaven National Laboratory aboard a G-1 aircraft (BNL G-1) made the bulk of the aircraft based isoprene measurements during TexAQS; both collected air samples in canisters for subsequent laboratory analysis. The NOAA/NCAR Electra typically sampled at an altitude of 600-700 m above ground level (AGL) in the late morning to early afternoon. The air samples typically filled the canister within 10 seconds, with the aircraft flying at a speed of approximately  $100 \text{ m s}^{-1}$ . Isoprene data were measured using both flame ionization and mass spectrometric detection. If both methods yielded results that were above the detection limit, of approximately 1 ppt, an average of both results was used. If one method yield a value above detection limit, and the other did not, the value above the detection limit was used (Personal communication, Donna Sueper, March 13, 2003).

A total of 18 G-1 Research flights were conducted between August 19 and September 11 in 2000. The canister samples were taken aboard the BNL G-1 at altitudes between 400 and 600 m AGL, in the morning to early afternoon. The samples were subsequently analyzed by gas chromatography ([ftp://aerosol.das.bnl.gov/pub/Houston00/HYDROCARBONS\\_V1.txt](ftp://aerosol.das.bnl.gov/pub/Houston00/HYDROCARBONS_V1.txt)). Sampling times were 10 seconds. For both aircraft, data on wind speed and directions were obtained.

### ***Methods for comparison of aircraft measurements and model predictions***

Air samples, collected by aircraft at 400-600 m AGL, are likely to contain isoprene that was emitted by land covers both immediately below the aircraft, and land covers in a broader area. For this work, the land area footprint was represented by identifying the model grid cells that the aircraft transited through during a 2-minute total period before, during, and immediately

after sample collection. Typically, an aircraft would fly through up to six-grid cells within 2 minutes of the collection of the air samples. A composite model prediction was obtained by weighting the data for each grid cell by the length of time that the aircraft spent in the grid cell during the 2-minute period selected for analysis.

## **RESULTS AND DISCUSSION**

Table 1, Table 2, Figure 2 and Figure 3 provide summaries of the comparisons between the model predictions and the aircraft data. The mean value of isoprene concentration measured by aircraft was 0.35 ppb; the corresponding modeled values averaged 0.28 ppb. As shown in Table 1 and Table 2, mean normalized bias and mean normalized gross error were  $-7\%$  and  $77\%$  for the NOAA dataset and were  $85\%$  and  $147\%$  for the BNL G-1 dataset. If the analysis is restricted to samples with measured concentrations above 0.1 ppb or 0.2 ppb, then the biases remain approximately constant, but the normalized gross errors of NOAA dataset are reduced to  $50\%$  and  $30\%$ , respectively. The normalized gross errors of G-1 dataset are reduced to  $70\%$  and  $85\%$ , respectively.

As shown in Figure 2, out of a total of 59 measurements made by the NOAA Electra, 24 show agreement between modeled and predicted values that were within a factor of two. In Figure 3, 22 out of a total of 52 measurements made by the BNL G-1 aircraft showed agreement within a factor of two. The outliers for the NOAA dataset were selected for additional analysis and were divided into two categories, moderate outliers and extreme outliers, as identified in Figure 2a. Most of the outliers show a negative model bias (modeled concentrations lower than observed concentrations). A variety of possible explanations for the biases were examined.

Table 1. Statistical summary of the comparison of predicted isoprene concentrations and NOAA aircraft observations

Date of sample collection	Number of pairs	Mean		MNB	MNGE
		Observed	Predicted		
8/25	14	0.37	0.33	1.7	77.
27	17	0.38	0.33	21.	86.
28	18	0.36	0.28	-34.	67.
30	10	0.27	0.13	-16.	80.
Total	59	0.35	0.28	-6.7 %	77. %

Samples with measured isoprene concentrations above 0.1 ppb

Date of sample collection	Number of pairs	Mean		MNB	MNGE
		Observed	Predicted		
8/25	9	0.51	0.50	48.	74.
27	11	0.53	0.44	-12.	29.
28	8	0.67	0.59	-5.3	63.
30	4	0.43	0.24	1.7	39.
Total	32	0.54	0.47	8.4 %	52. %

Samples with measured isoprene concentrations above 0.2 ppb

Date of sample collection	Number of pairs	Mean		MNB	MNGE
		Observed	Predicted		
8/25	4	0.96	0.76	-23.	33.
27	6	0.77	0.68	-10.	27.
28	5	0.78	0.87	-18.	35.
30	1	1.19	0.30	-75.	75.
Total	16	0.85	0.74	-11. %	34. %

$$\text{Mean Normalized Bias (MNB)} = \frac{1}{N} \sum_1^N \left( \frac{\text{Pr ed.} - \text{Obs.}}{\text{Obs.}} \right) \cdot 100\%$$

$$\text{Mean Normalized Gross Error (MNGE)} = \frac{1}{N} \sum_1^N \left( \frac{|\text{Pr ed.} - \text{Obs.}|}{\text{Obs.}} \right) \cdot 100\%$$

Where N is the number of observations

Table 2. Statistical summary of the comparison of predicted isoprene concentrations and BNL G-1 aircraft observations

Date of sample collection	Number of pairs	Mean		MNB	MNGE
		Observed	Predicted		
8/26	25	0.385	0.39	61.	138.
29	27	0.23	0.25	108.	156.
Total	52	0.30	0.32	85. %	147. %

Samples with measured isoprene concentrations above 0.1 ppb

Date of sample collection	Number of pairs	Mean		MNB	MNGE
		Observed	Predicted		
8/26	12	0.64	0.71	53.	133.
29	17	0.32	0.31	20.	77.
Total	29	0.45	0.47	34. %	100. %

Samples with measured isoprene concentrations above 0.2 ppb

Date of sample collection	Number of pairs	Mean		MNB	MNGE
		Observed	Predicted		
8/26	7	0.77	1.12	133.	187.
29	7	0.46	0.46	0.8	68.
Total	14	0.62	0.79	67. %	127. %

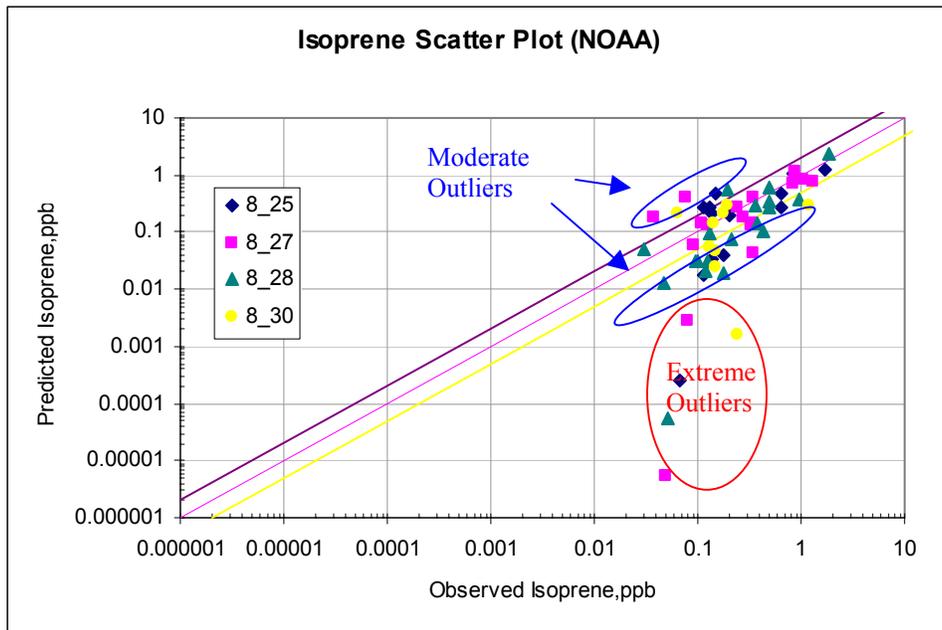


Figure 2a. Scatter plot of predicted and observed isoprene concentrations (NOAA dataset)

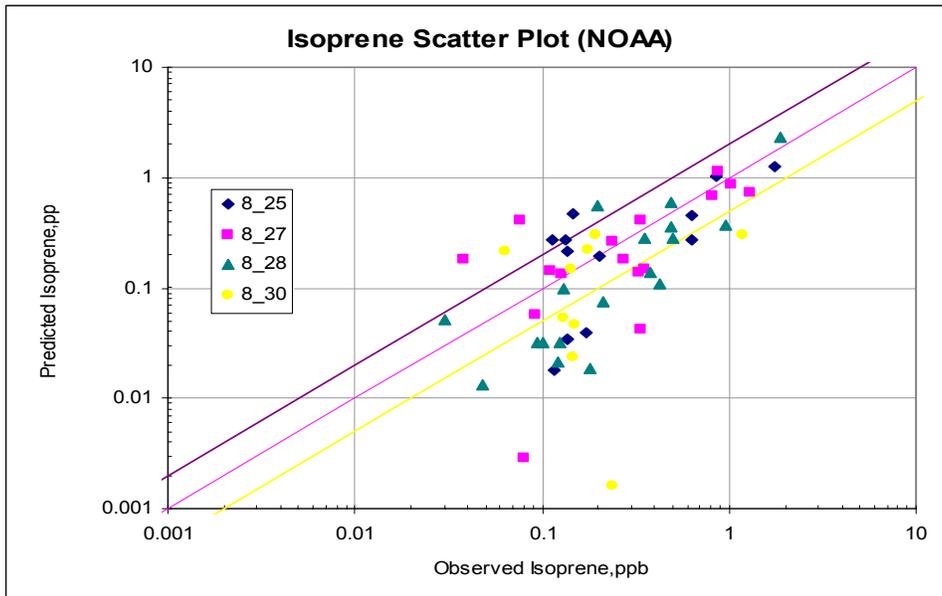


Figure 2b. Scatter plot of predicted and observed isoprene concentrations (NOAA dataset, larger scale)

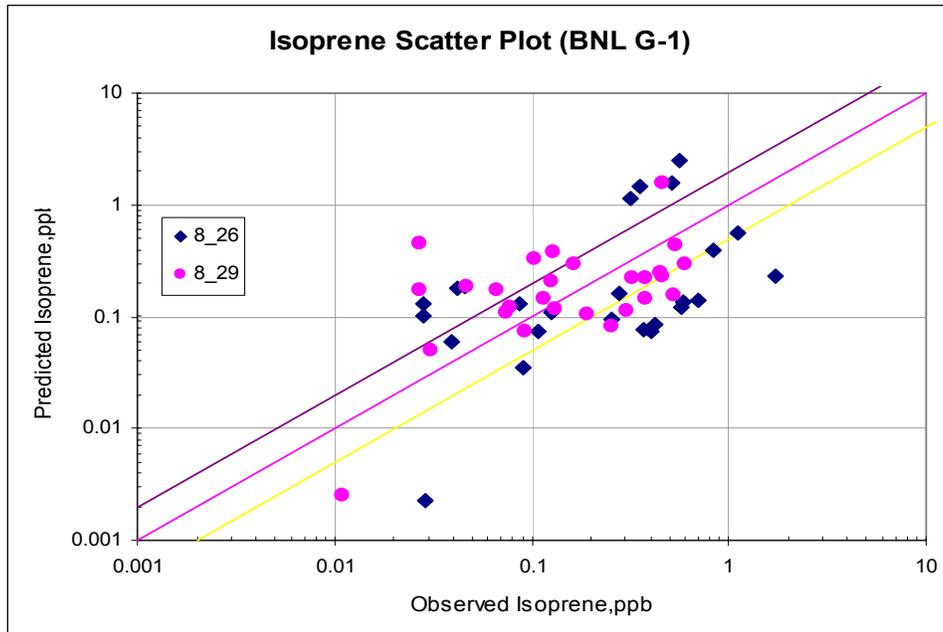


Figure 3a. Scatter plot of predicted and observed isoprene concentrations (BNL G-1 dataset)

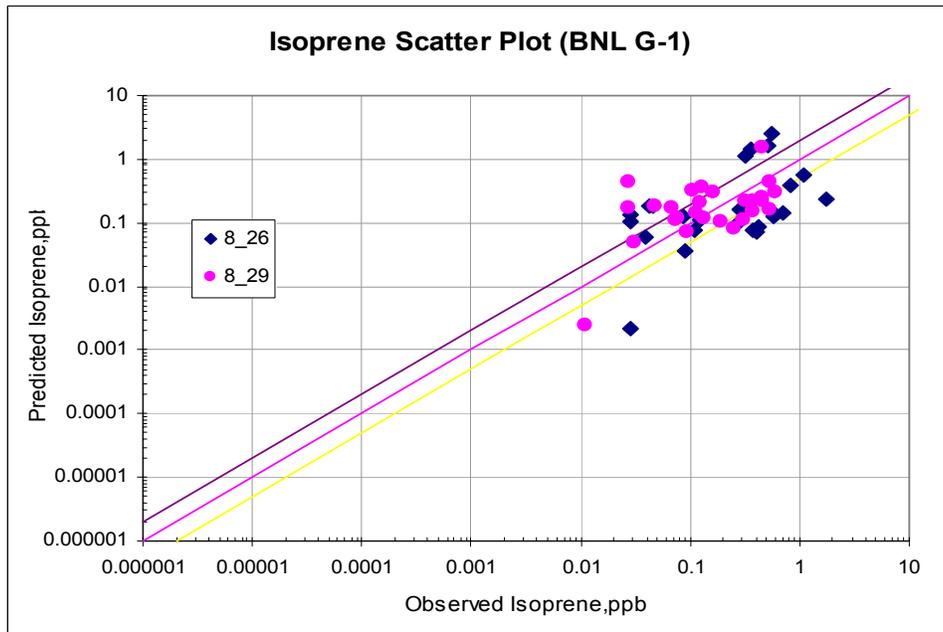


Figure 3b. Scatter plot of predicted and observed isoprene concentrations (BNL G-1 dataset, smaller scale)

Possible reasons for under-prediction of observed concentrations in the model could be over-prediction of cloud cover or under-prediction of temperature in the model. To investigate the impact of cloud cover and temperature assumptions on predicted isoprene concentrations, two sets sensitivity analyses were performed. In one set of sensitivity analyses, emissions were recalculated based on an assumption of no cloud cover. These emission estimates were compared to the emission estimates using cloud cover based on GOES satellite data. In another set of sensitivity studies, emissions were estimated using surface temperatures calculated using the MM5 meteorological model. These emission estimates were compared to the emission estimates using interpolated National Weather Service temperature data. The results are shown in Figure 4. The comparisons show that varying assumptions about cloud cover or varying surface temperature generally had relatively small impacts on predicted emissions (<10-20%), compared to the observed discrepancies between modeled and observed concentrations. The comparisons shown in Figure 4 are for emissions integrated over the modeling domain. Point estimates of isoprene emissions were also made at the locations of the aircraft measurements. The varying assumptions about cloud cover or surface temperature also had relatively small impacts on point emission estimates (<10-20%).

Another possible source of discrepancy between modeled and observed concentrations could be missing anthropogenic sources in the model. The anthropogenic sources of isoprene are summarized in Table 3. Although the magnitude of the anthropogenic emissions is significantly lower than the magnitude of the biogenic emissions, the point source isoprene emissions are spatially concentrated, so it is possible that temporal emission variability for the isoprene point sources could lead to discrepancies between modeled and observed concentrations. Comparison of the locations of the outliers with the locations of the point sources suggests that a few of the outliers might be due to industrial point sources.

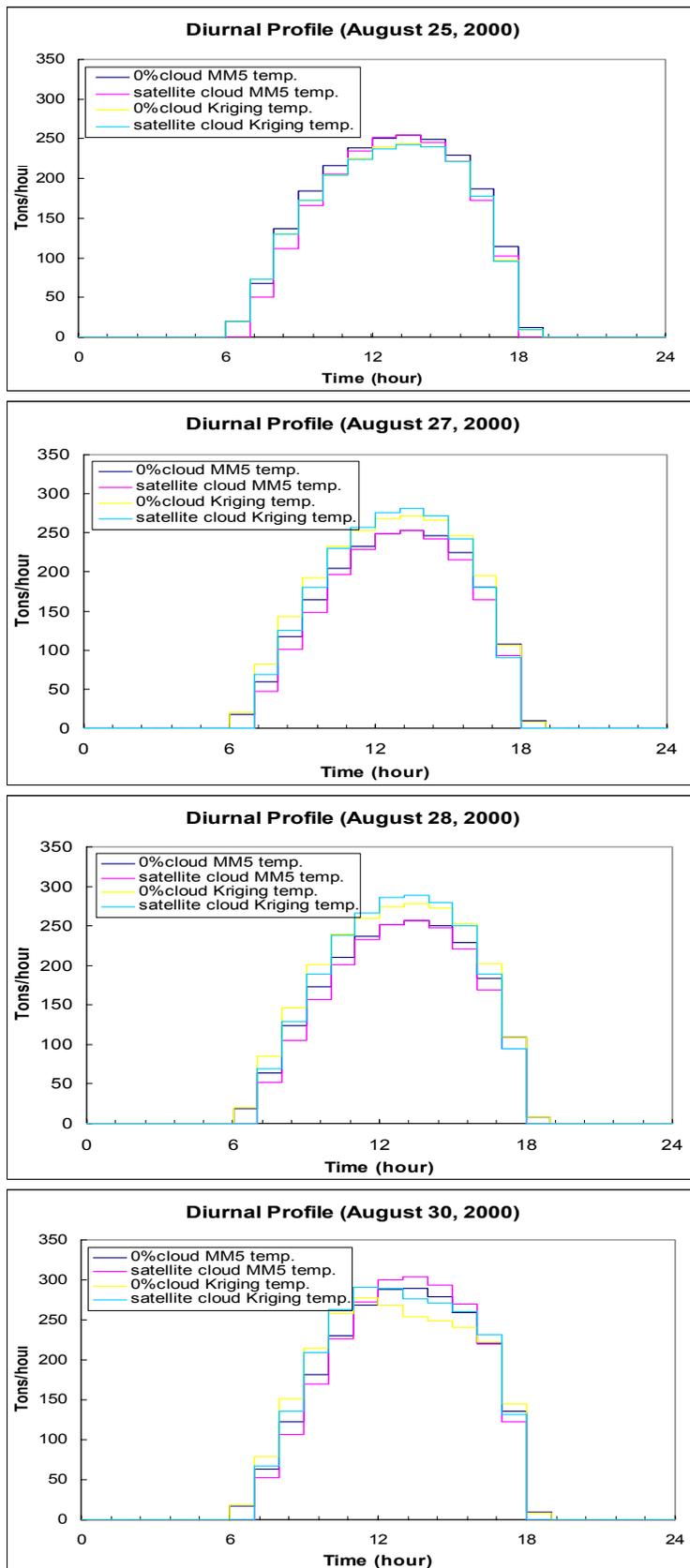


Figure 4. Temporal variations in estimated isoprene emissions using different assumptions about cloud cover and different surface temperature estimates (MM5 = surface temperatures drawn from MM5 simulations; Kriging = surface temperatures estimated from NWS temperatures interpolated using a Kriging algorithm; satellite cloud = cloud cover determined from GOES satellite data; 0% cloud cover = clear sky assumption). The base case simulation uses NWS surface temperatures interpolated using a Kriging algorithm and cloud cover determined using GOES satellite measurements (satellite cloud, Kriging temp.), and gives the highest emission estimates on August 27 and 28.

Table 3. Anthropogenic sources of isoprene in Harris County

Point Source	Emissions (tons day <sup>-1</sup> )	Percent (%)
Chemical Manufacturing	0.21714	54.46
Secondary Metal Production	0.00002	0.005
Mineral Products	0.00048	0.12
Petroleum Industry	0.02594	6.51
Fabricated Metal Products	0.00283	0.71
Printing and Publishing	0.00056	0.14
Surface Coating Operations	0.00053	0.13
Petroleum Product Storage at Refineries	0.08927	22.39
Petroleum Liquids Storage (non-Refinery)	0.05041	12.64
Organic Chemical Storage	0.00163	0.41
Organic Chemical Transportation	0.00771	1.93
Organic Solvent Evaporation	0.00218	0.55

	Emissions (tons day <sup>-1</sup> )	Percent (%)
Point sources	0.6772	70.26
Mobile sources	0.2303	23.89
Area sources	0.0013	0.13
Off-road sources	0.0551	5.72
Total	0.9639 (= 874 kg day <sup>-1</sup> )	100

For example, for the sample collected at 10:39 AM on August 30 near industrial sources, the observed concentration was 1.19 ppb while the model prediction was 0.30 ppb. In principle, the industrial emissions would be accounted for in the model predictions; however, recent analyses have shown that temporal variability in point source industrial emissions can be significant in the Houston/Galveston area (Allen *et al.*, 2004).

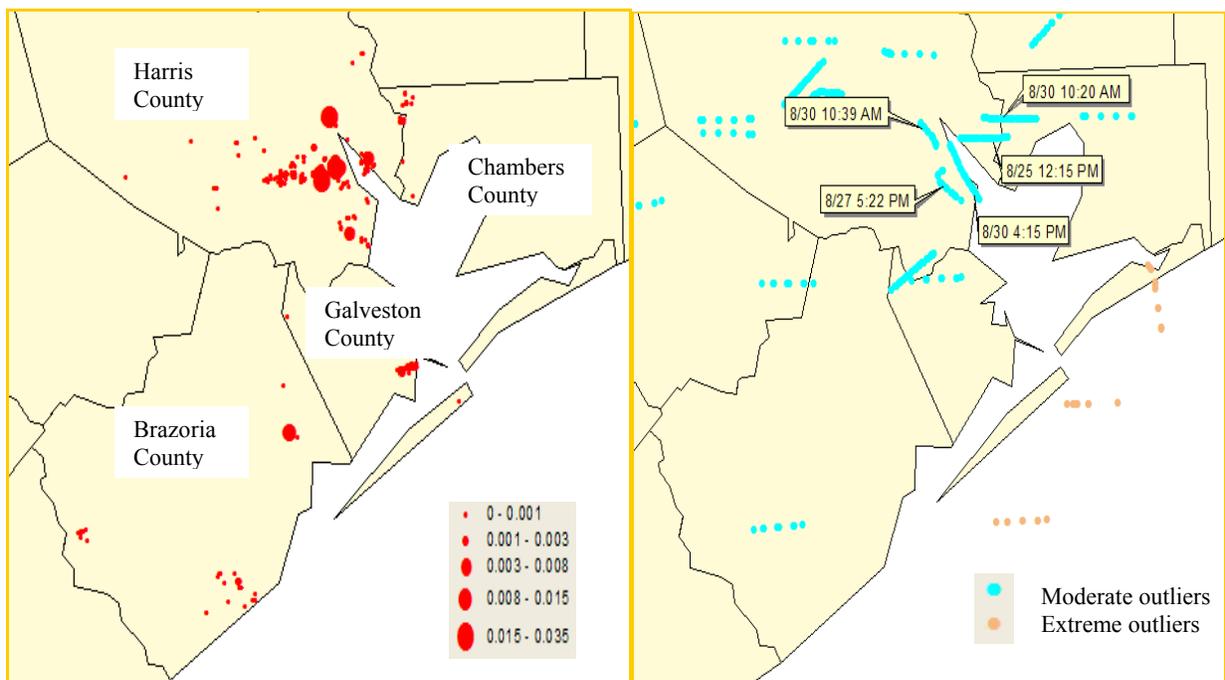


Figure 5. Isoprene emissions from point sources ( $\text{tons day}^{-1}$ ) and locations at which isoprene concentrations were under-predicted

Another possible source of discrepancy between modeled and observed concentrations is incorrect characterization of land covers. If the discrepancies between modeled and observed concentrations are due to land cover inaccuracies at certain locations, then there should be a consistent overestimate or underestimate of concentration at those locations. As shown in Figure 6, there are certain locations, not associated with industrial sources, where concentrations are consistently overestimated or underestimated. However, there are other locations, for example

measurements over the Gulf of Mexico (see Figure 5), where the land cover is not in doubt, but significant discrepancies can exist.

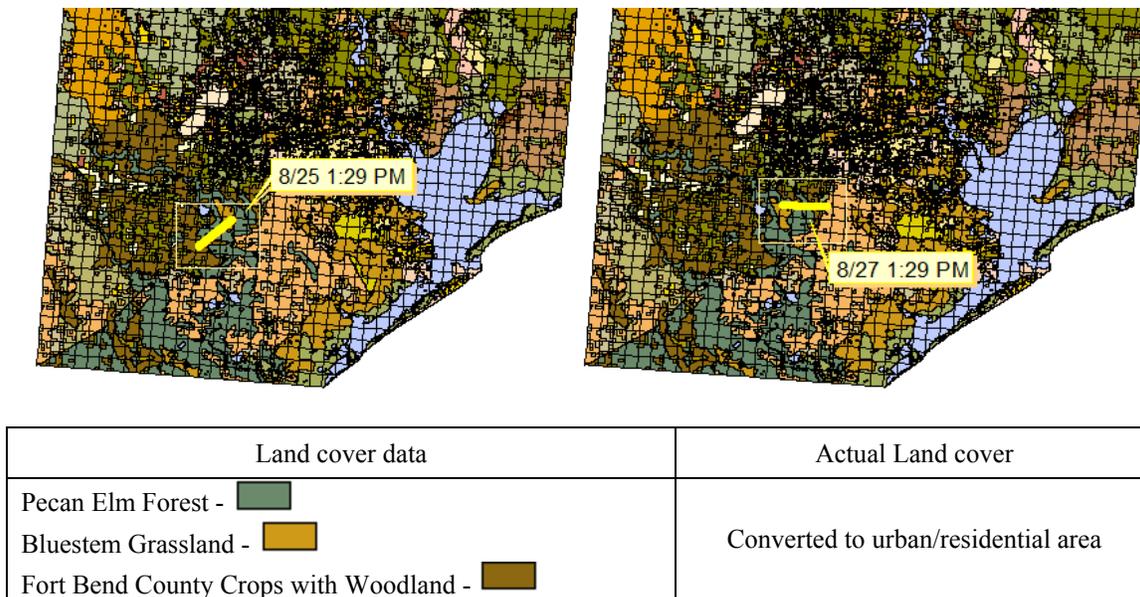


Figure 6. Land covers at locations where isoprene concentrations were consistently overestimated; in the maps, the aircraft flight track, in yellow, is superimposed on land cover maps used in the emission estimation. The land covers used in the model at these locations were ground truthed, resulting in the comparisons reported.

Another potential source of systematic under-prediction of isoprene concentration is inadequate vertical mixing or inadequate growth of the mixed layer in the model. For the moderate outliers, Figure 7 shows that the model was generally predicting a large gradient in isoprene concentration as a function of height. Some of these moderate outliers are model over-predictions; others are under-predictions. For the data shown in the lower two panels of Figure 7, inaccurate mixing height growth may account for model discrepancies, while for other observations inaccurate vertical mixing does not appear to be the dominant cause of uncertainty for the moderate outliers.

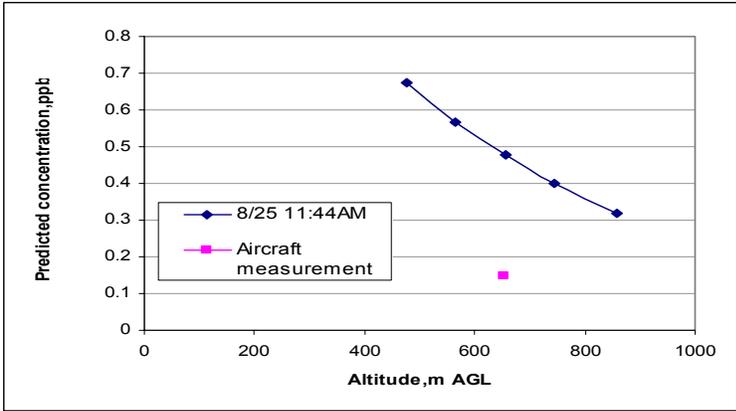
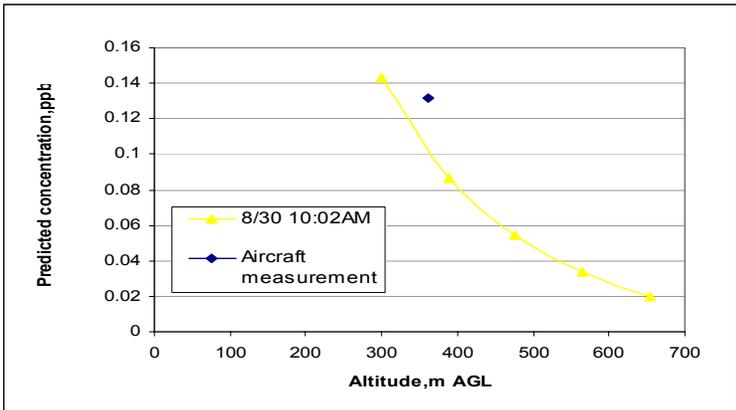
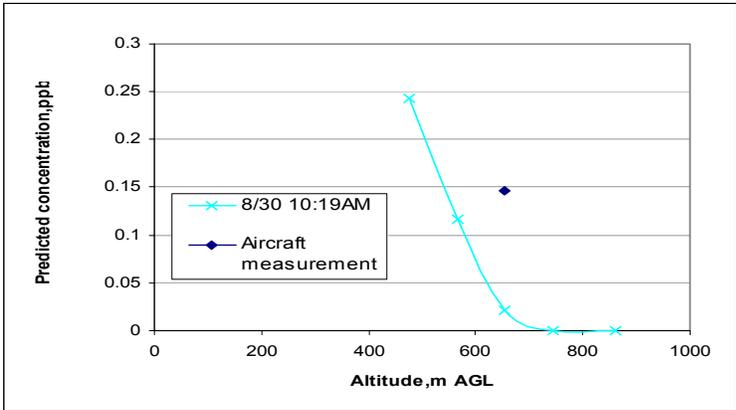
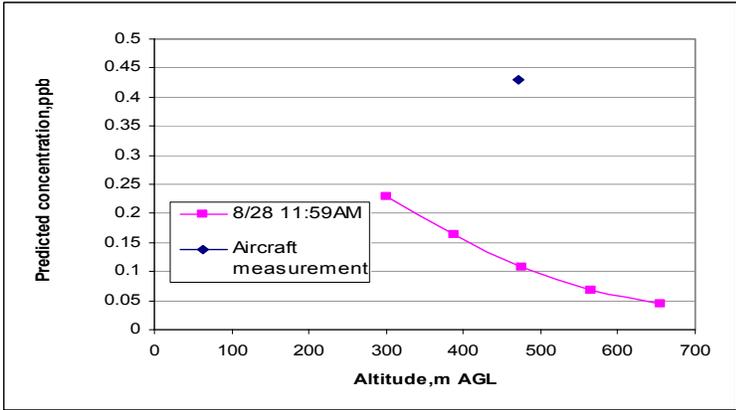


Figure 7. Moderate outliers which were collected in the morning (before noon): The isoprene concentrations of two layers above and below the layer where the sample was collected are plotted, along with the aircraft measurement.



## CONCLUSIONS

Isoprene concentration measurements made in southeastern Texas during August 2000 were compared to modeled concentrations. Normalized gross errors were in the range of 30-80% with a normalized bias of approximately -10%. Normalized gross errors tended to decrease at higher observed concentrations. The greatest discrepancies between modeled and predicted concentrations were due to model under-predictions of observed concentrations. Possible causes for the discrepancies include inaccurate characterization of land covers, inaccuracies in point source isoprene emission estimates, and the characterization of horizontal and vertical transport of isoprene in the model. Sensitivity analyses suggest that the methods used for estimating surface temperatures and cloud cover do not introduce enough uncertainty to explain the variations between model predictions and observations.

## REFERENCES

- Allen, D., Murphy, C., Kimura, Y., Vizuete, W., Edgar, T., Jeffries, H., Kim, B.U., Webster, M., Symons, M., 2004. Variable Industrial VOC Emissions and their impact on ozone formation in the Houston Galveston Area, Report submitted to Texas Environmental Research Consortium, available at: <http://www.harc.edu/harc/Projects/AirQuality/>
- Carter, W.P.L., 1996: Condensed atmospheric photooxidation mechanisms for isoprene. *Atmospheric Environment* 30 (24), 4275-4290
- Environ International Corporation (Environ), 2002. Final Report: Biogenic VOC emission estimates for the TexAQS 2000 Emission inventory: Estimating emissions during periods of drought and prolonged high temperatures and developing GloBEIS3, available at: <http://www.globeis.com/data/globeis3report.11apr02.pdf>
- Fehsenfeld, F., Calvert J., Fall R., Goldan P., Guenther A., Hewitt C., Lamb B., Liu S., Trainer M., Westberg H., and Zimmerman P., 1992. Emissions of volatile organic compounds from vegetation and the implications for atmospheric chemistry. *Global Biochemical Cycles* 6, 389 – 430.
- Geron, C., Guenther, A., Sharkey, T., Arnts, R., 2000. Temporal variability in the basal isoprene emission factor. *Tree Physiology* 20, 799-805.
- Guenther, A., Hewitt C., Erickson D., Fall R., Geron C., Graedel T., Harley P., Klinger L., Lerdau M., McKay W., Pierce T., Scholes B., Steinbrecher R., Tallamraju R., Taylor J., and Zimmerman P., 1995. A global model of natural volatile organic compound emissions, *Journal of Geophysical Research* 100 (D5), 8873 – 8892.
- Guenther, A., Geron C., Pierce T., Lamb B., Harley P., and Fall R., 2000. Natural emissions of non-methane volatile organic compounds, carbon monoxide, and oxides of nitrogen from North America. *Atmospheric Environment* 34, 2205 – 2230.

- Helmig, D., Klinger L., Guenther A., Vierling L., Geron C., and Zimmermann P., 1999. Biogenic volatile organic compound emissions (BVOCs) I. Identifications from three continental sites in the U.S.. *Chemosphere* 38, 2163 – 2187.
- Kempf, K., Allwine E., Westberg H., Claiborn C., and Lamb B., 1996. Hydrocarbon emissions from spruce species using environmental chamber and branch enclosure methods. *Atmospheric Environment* 30, 1381 – 1389.
- König, G., Brunda M., Puxbaum H., Hewitt C., Duckham C., and Rudolph J., 1995. Relative contribution of oxygenated hydrocarbons to the total biogenic VOC emissions of selected Mid-European agricultural and natural plant species. *Atmospheric Environment* 29, 861 – 874.
- Petron, G., Harley, P., Greenberg, J., Guenther, A., 2001. Seasonal temperature variations influence isoprene emission. *Geophysical Research Letters* 28 (9), 1707-1710.
- Sharkey, T.D., Singsaas, E.L., Lerdau, M.T., Geron, C., 2000. Weather effects on isoprene emission capacity and applications in emissions algorithms. *Ecological Applications* 9, 1132-1137.
- Texas Air Quality Study 2000. available at:  
<http://www.utexas.edu/research/ceer/texaqs/index.html>
- Texas Natural Resource Conservation Commission, 2000. The State Implementation Plan for the Control of Ozone Pollution: Attainment Demonstration for the Houston/Galveston Ozone Nonattainment Area. P.O. Box 13087, Austin, Texas 78711-3087., available at:  
[http://www.tnrcc.state.tx.us/air/aqp/airquality\\_photomod.html#section4](http://www.tnrcc.state.tx.us/air/aqp/airquality_photomod.html#section4).
- Vizuete, W., V. Junquera, E. McDonald-Buller, G. McGaughey, G. Yarwood, and D. T. Allen, 2002. Effects of Temperature and Land Use on Predictions of Biogenic Emissions in Eastern Texas, *Atmospheric Environment* 36, 3321-3337.
- Wiedinmyer, C., Strange I., Estes M. Yarwood G., and Allen D., 2000. Biogenic hydrocarbon emission estimates for North Central Texas. *Atmospheric Environment* 34, 3419 – 3435.
- Wiedinmyer, C., Guenther, A., Estes, M., Strange, I., Yarwood, G., Allen, D., 2001. A land use database and examples of biogenic isoprene emission estimates for the state of Texas, USA. *Atmospheric Environment* 35, 6465-6477.
- Winer, A., Arey J., Atkinson R., Aschmann S., Long W., Morrison C., and Olszyk D., 1992. Emission rates of organics from vegetation in California's Central Valley. *Atmospheric Environment* 26, 2647 – 2659.
- Yarwood, G., G. Wilson, S. Shepard, and A. Guenther. 1999a. User's Guide to the Global Biosphere Emissions and Interactions System – Version 2.1. 101 Rowland Way, Suite 220, Novato, California, available at: <http://www.globeis.com>
- Yarwood, G., G. Wilson, C. Emery and A. Guenther 1999b Development of the GloBEIS – A State of the Science Biogenics Emissions Modeling System. Final Report to the Texas Natural Resource Conservation Commission, 12100 Park 35 Circle, Austin, Texas 78753.