Review of the Effects of Drought and High Temperature on Biogenic Emissions

And

Future Research Efforts in Texas

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Task 1A. Review the existing scientific evidence of the effects of drought and high temperatures on biogenic VOC emissions.

I. Drought studies

The biogenic emission models currently used for Texas (e.g., GLOBEIS 2.2) do not account for the influence of drought on VOC emissions. Studies that have been conducted to investigate the influence of drought on biogenic VOC emissions are described in this section. It is well known that drought will impact some plant physiological processes. The physiological responses to moderate drought include significant reductions in stomatal conductance and photosynthesis rates. Extreme drought reduces these rates to zero and results in senescence (the plant drops its leaves) in some plants. Specific responses vary considerably among different species. For example, some oak species are fairly drought resistant while others are sensitive to drought conditions.

Tingey et al. (1981) conducted the first investigation of the impact of drought on isoprene emissions. They used live oaks (Quercus virginiana) that are an important component of some landscapes in Texas and the southeastern United States. The oaks were seedlings grown in pots in a greenhouse. The expected large decrease in photosynthesis was surprisingly accompanied by almost no change in isoprene emission.

The next drought study was an investigation of the impact of water stress on Kudzu (Pueraria lobata) by Sharkey and Loreto (1993). Kudzu is an introduced vine that is grown commercially in some areas (it is a nitrogen fixer and can be used for forage) and is common in disturbed landscapes in the southeastern United States. They found that photosynthesis rates would drop to zero after about 6 days of withholding water from the potted kudzu vines. During this time, isoprene emissions actually increased slightly. They report that isoprene emissions did decrease "when the stress was severe" but they do not describe these results any further. They then began to water the plants again and found that after 4 days the photosynthesis rates were back to their pre-stress levels while isoprene emission increased to level that was 5 times higher than pre-stress levels and remained at this higher level until the experiment was ended 12 days later. They report that the impact of water stress on isoprene was more pronounced when measured at higher temperatures. One factor that Sharkey and Loreto (1993) fail to note, however, is that the pre-stress kudzu emission rate that they report is about a factor of five lower than what is typically observed. It seems likely that isoprene emission had not been fully induced in these plants until after the stress treatment. If this is the case then these observations suggest that kudzu has a normal isoprene emission rate after recovery from drought rather than extremely high isoprene emissions after drought. Sharkey and Loreto (1993) also refer to their own unpublished data on potted velvet bean (Phaseolus acutifolius) plants where they observed a factor of 2-3 increase in isoprene emission following rapid water stress.

Fang et al. (1996) investigated the influence of drought on isoprene emissions from one-year old sweetgum (Liquidambar styraciflua) seedlings. Previously unstressed plants were exposed to nine successive drought and recovery cycles over a four-month period. Each drought was taken to the point of leaf wilting and then they began re-watering. Control plants were

watered at 2-3 day intervals throughout the experiment. Leaf predawn xylem water potential was, on average, 0.5 MPa lower in the drought stressed seedlings than in the well-watered control seedlings. These sweetgum were fairly drought resistant and were able to recover from the drought cycles. The investigators concluded that this was a result of their ability to cease growth and reduce their water use and note that sweetgum is known to inhabit dry sites that are exposed to drought. The results from the different drying cycles varied, but in general, and in agreement with earlier studies, isoprene emission was considerably less sensitive to drought than photosynthesis. In some cases, isoprene emission increased slightly at the beginning of a drying cycle. It was even more apparent that isoprene emission could recover much more quickly than photosynthesis. The behavior of the control group demonstrated the difficulty in drawing conclusions from these measurements since isoprene emission from these well-watered plants varied by as much as 50% over the course of a drying cycle. This indicates that factors other than the drying could have contributed significantly to the observed change in emissions from the drought treated plants.

NCAR and Texas A&M scientists investigated the influence of drought on isoprene emissions from post oak (Quercus stellata) that dominates some landscapes in Texas and other southern states (Guenther et al. unpublished data). They found that isoprene emissions were nearly constant except under conditions that would correspond with severe drought (wilted leaves).

Guenther et al. (1999a) investigated the influence of limited water availability on isoprene emissions from native plants at the semi-arid La Copita Texas research station. They compared gas exchange and water relations of adult *Berberis trifoliolata* and *Condalia hookeri* plants that had been growing in plots receiving supplemental water (ca. 30 cm of water every 2-4 weeks since May 1994) to plants receiving only natural rainfall (Figure 2). At the time of the measurements (late September 1994), there had been 81 mm of natural rainfall in August and 46 mm in September, of which 5 mm had fallen during the 2 weeks preceding the measurements. Differences in levels of plant water stress between the irrigated and non-irrigated plots were reflected in higher pre-dawn water potentials among plants on the irrigated plots (mean water potential = - 0.9 and - 0.7 MPa for *Condalia* and *Berberis,* respectively) compared to those on the non-irrigated plots (mean water potential = -2.0 and - 1.9 MPa). Although drought stress reduced stomatal conductance by 30 to 50% in both species and reduced net photosynthesis rates by 40% in *Berberis* compared to that of well-watered plants, leaf level isoprene emission rates were not affected.

In summary, there have been six studies of the influence of drought on isoprene emission. This includes four studies that have been published in peer reviewed journal articles. Four of these studies were short term studies (less than two months) using potted plants, one was a longer term study using potted plants and the sixth used field grown plants under natural Texas style drought. Investigations using potted plants and laboratory measurements provide valuable information from which to build hypothesis but it is widely recognized that these studies often generate results that differ from those observed using field grown adult specimens in their natural environment. It is also often the case that plant physiological responses to drought will vary for different plant species since different species have different growth strategies. Thus it is not yet possible to comprise any definitive descriptions of isoprene emission response to drought from

the six studies described above. However, there is a general consensus (Fuentes et al. 2000, Guenther et al. 2000) that extreme and extended drought will lower the isoprene emission capacity of a plant. Lower emissions will certainly occur as a drought deciduous plant loses its leaves. We cannot yet quantitatively describe the decrease expected for other plants due to the limited observations. All of the above studies attempted to study the influence only of drought but it is nearly certain that other factors, important for controlling isoprene emission, varied during the studies. As is discussed below, one factor that was almost certainly varying was the antecedent leaf temperature, which would act to balance the decrease in emission capacity due to lower water potential.

Even less is known about how other emissions will respond to drought but it is likely that emissions of some VOC compounds will be less responsive while others are more responsive. Bertin and Staudt (1996) withheld water from young potted Quercus ilex trees and found that monoterpene emissions were reduced only after severe drought. Monoterpenes are not stored in Q. Ilex and their light dependent production and emission pattern is similar to isoprene. The emissions of monoterpenes that have been stored in plant tissues (e.g., from the pine trees of east Texas) are likely to be very unsensitive to drought. Lerdau et al. (1994) observed very low afternoon water potentials for Ponderosa pine (Pinus ponderosa) that resulted in sharp declines in water potential and photosynthesis but did not appear to influence monoterpene emissions. Several investigators have used enclosure systems to investigate oxygenated VOC emissions (e.g., Kesselmeier et al., MacDonald and Fall, Guenther et al., unpublished data) and have observed a strong correlation between emissions and stomatal conductance. This suggests that the lower stomatal conductance observed with drought conditions might lead to large decreases in these emissions. On the other hand, some oxygenated VOC emissions appear to be greatly increased by stress and so drought might increase their emissions (Guenther et al., unpublished data).

II. Prolonged high temperatures

Biogenic VOC emissions are very sensitive to changes in temperature and all efforts to model these emissions have included some algorithm describing temperature dependence. In most cases, the temperature dependence algorithm simulates the only response that is observed when temperature changes fairly quickly (over a time scale of an hour or less). Other plant physiological processes (e.g., photosynthesis) are sensitive to changes in the temperature history of the plant so it is not surprising that isoprene emission would also be similarly influenced. Efforts to characterize this effect are described in this section.

Sharkey et al. (2000) used a temperature and light controlled enclosure system to repeatedly measure isoprene emissions at a leaf temperature of 30 ^{o}C and PAR flux of 1000 µmol m-2 s-1. They measured emissions on leaves near the top of a 30-m white oak (Quercus alba) at the Duke forest research site and a 20-m red oak (Quercus rubra) tree. Their results demonstrated that, for the same temperature and PAR conditions, isoprene emission varied considerably more than photosynthesis. They tested the possibility that the variability was correlated with the temperature and/or PAR of the previous one, two four or seven days. They found that the product of temperature and PAR over the past two days had the strongest

correlation (r2=0.95) although either temperature or PAR alone was also highly correlated (r2 > 0.86). The slope of the product of temperature and PAR vs. emission was 0.066. The correlation with PAR alone was always less than that for temperature alone. The correlation for temperature alone was highest with the past two days (r2=0.92) but was also significant for one, four and seven days (0.72 > r2 > 0.82).

Geron et al. (2000) extended the investigation initiated by Sharkey et al. (2000) with additional measurements on the oak (Q. alba) tree at the Duke forest site. In this study, 8 leaves were investigated over the course of a season. They collected a much larger database and reduced genetic and diurnal variability by measuring the same set of leaves at the same time of day. They correlated the apparent emission factor with the light and temperature of the previous 1 through 96 hours before the measurement. They found the highest correlation (r2 >0.8) for the product of the mean temperature and light of the previous 18 hours. The correlation with temperature and light averaged over the past 48 hours, which gave the maximum correlation for the Sharkey et al. (2000) data, was considerably lower (r^2 of about 0.5). It is unfortunate that leaf temperature measurements were not available for this analysis. Since both light and ambient air temperature influence leaf temperature, it is possible that the higher correlation observed using both of these factors is due to their combined effect on leaf temperature.

Several investigators have examined their above canopy flux measurements (REA or eddy covariance) to see whether isoprene emission was elevated, beyond what would be expected using the Guenther et al. (1993) temperature algorithm, after a period of several warm days (Fuentes et al. BOREAS; Lamb et al., personal communiction; Guenther et al., unpublished data). In another case, Fuentes et al. (1999) observed isoprene emissions decreasing to rates lower than expected using the Guenther et al. (1993) algorithm after exposure to abnormally low temperatures.

Petron e t al. 2001 investigated the influence of long-term variations in growth temperature on isoprene emission rates from oak (*Quercus macrocarpa*) leaves under controlled environmental conditions. Trees were installed in a growth chamber and exposed to a series of daytime temperatures that were varied after a period of 3-6 weeks. Emission capacity doubled when growth temperature was increased from 25 to 30 ^{o}C. Ten days after the growth temperature was returned to 20 ^{o}C, isoprene emission capacity fell to 25 to 50% of its peak value. When growth temperature was returned to 30 ^{o}C, emission capacity doubled within 5 hours and continued to increase over several days.
Guenther et al. (1999) used these data to develop an emission algorithm that they used in a regional model of emissions from Central Africa.

In summary, it is clear that leaf temperature of past hours is important in determining isoprene emission rates. The mechanism determining this control is not known but there are three limited data sets available for developing empirical relationships. Curiously, each of the three available data sets suggests a different time scale for antecedent temperature influence: 18, 48 and 360 hours. A possible explanation for this discrepancy is that the influence of antecedent temperature operates over several different time scales.

III. Drought and high temperatures

There are several field studies that were probably influenced by the combined effect of drought and prolonged high temperatures but the study designs do not provide enough information to characterize their impacts. For example, Martin et al. 1999 used a field enclosure system to estimate emission factors of isoprenoid and oxygenated VOC from some of the dominant tree species of New Mexico. The trees were sampled only once with the exception of one individual tree, a cottonwood (Populus fremontii), that was sampled in May, which was characterized by unusually high temperatures following a severe sustained drought, and the following September, during lower temperatures and after significant summer precipitation. The results show that the emissions of at least some oxygenated VOC (e.g., formaldehyde, acetic acid) were considerably lower during the May (drought stressed) period. Isoprene emission rates were similar during the two periods although the rate of increase with temperature was higher for the May period. Since there were no reported measurements of water potential, stomatal conductance or photosynthesis, it is difficult to tell how strongly the cottonwood was influenced by the drought since it is possible that the tree had access to ground water.

Geron and Guenther (unpublished data) investigated VOC emissions from desert shrubs at the Nevada Test Site research area. They found that the one isoprene emitting species at this site, mormon tea (Ephedra nevadensis) could maintain very high emission rates for an extended period of time (> 2 hours) at temperatures exceeding 55C. This was surprising since the expected behavior for isoprene emission is very low emissions at temperatures above 50C. Similar behavior has been observed with shrub live oak (Quercus turbinella) in the high desert of central New Mexico (R. Martin, personal communication).

Lerdau and Keller 1997 measured tropical species using enclosure measurements during wet season and dry season and found no significant difference when measured under the same environmental conditions. Unfortunately, they did not measure photosynthesis. They also noted that the temperature of maximum isoprene emission was higher than what had been observed previously. They attributed this to a difference between temperate and tropical plant species.

Guenther et al. 1999 used REA and eddy covariance methods to measure above canopy fluxes of isoprene, CO2 and water vapor above a central African rainforest at the end of the dry season and the end of the wet season. They found that with the same above canopy conditions, isoprene was about a factor of two higher, and net ecosystem CO2 and water fluxes were about a factor of two lower during the end of the dry season. They suggested that leaf temperatures, although not measured, were probably much higher due to the lower stomatal conductance. Preliminary measurements from Amazonian rainforests (Guenther et al., unpublished data) suggest that a similar pattern occurs in other tropical regions.

Field measurements by Steinbrecher et al. 1997 in the Mediterranean region indicated isoprene emission from *Quercus pubescens* exhibited a “mid-day depression” pattern typical of that observed for stomatal conductance and photosynthesis. These observations differ from other observations that indicate no stomatal control over isoprene emissions. However, the difference could be due to long-term water limitations and should be investigated further.

Goldstein and Schade (2001) described canopy-scale, continuous, long-term flux measurements of several oxygenated VOC above a pine plantation in California. The late summer measurements are representative of moderately drought stressed conditions. They observed large daytime emissions (~ 1.3 mg m-2 h-1) of methanol and methyl butenol and about a factor of 5 lower emissions of acetone, ethanol and acetaldehyde. They report that several compounds (acetone, methanol, ethanol) appear to be influenced by relative humidity. They suggest that emissions of these compounds and acetaldehyde are controlled by stomatal conductance that implies that drought would decrease these emissions. They found that moisture could play a significant role in net ecosystem acetone emission (with higher emissions associated with wetter conditions) and note that this might be dominated by emissions from leaf litter and soil.

In summary, some field observations suggest that it is likely that drought and prolonged high temperatures influence biogenic VOC emissions but existing data are not suitable for developing quantitative relationships. One obvious impact is the decrease in emissions expected after a drought deciduous plant loses its leaves. For other plants, the existing observations suggest that 1) isoprene emission capacity and photosynthesis ultimately decrease with reduced water availability, 2) the apparent isoprene emission capacity and the temperature of maximum emission both increase when drought-induced decreases in stomatal conductance increase leaf temperature, and 3) isoprene emission rates are increased due to these higher leaf temperatures.

Task 1B. Based on the studies described by Task 1A, recommend methods to incorporate into GLOBEIS 2.2 to simulate biogenic emissions during conditions of moderate and extreme drought. Also identify sources of any driving variables required for these methods.

I. Prolonged high leaf temperatures

There are currently three choices available for estimating the influence of prolonged high temperatures on isoprene emission rates. The methods are described by equations 1 (Sharkey et al. method), 2 (Geron et al. method), and 3 (Guenther et al. method). Additional studies are required before we can determine which of these equations (or some combination of them) best simulates the impact of antecedant temperatures. At present, the best option is to use all three equations and consider the range of results as an indicator of the magnitude of the effect associated with this controlling factor.

The Guenther et al. (1999) method is presented in the form of an algorithm that can easily be incorporated into an emission model:

$$\gamma_T = E_{opt}\, C_{T2} \exp(C_{T1}\, x)/[C_{T2}-C_{T1}\{1-\exp(C_{T2}\, x)\}] \qquad (1a)$$

where $x = [(1/T_{opt})-(1/T)]/R$, T is current leaf temperature (K), R is the gas constant (=0.00831), E_{opt} is the maximum normalized emission capacity, T_{opt} is the temperature at which E_{opt} occurs, and the empirical coefficients C_{T1} (=95) and C_{T2} (=230) represent the energy of activation and deactivation,

respectively. The maximum normalized emission capacity and the temperature at which it occurs are estimated as

$$E_{opt} = 1.9 \text{ x } \mathrm{Exp}(0.125 * (T_{360} - 301)) \qquad (1b)$$

and

$$T_{opt} = 312.5 + 0.5 *(T_{360} - 301) \qquad (1c)$$

where T_{360} is the mean temperature (K) of the past 360 hours (15 days). Equation 3a is nearly equivalent to the algorithm of Guenther et al. (1993) for $E_{opt} = 1.9$ and $T_{opt} = 312.5$ K.

Geron et al. (2000) suggested using their results in the following algorithm:

$$\gamma_T = \gamma_{T1} [1 + .0000682 (P_{18}T_{18} - PT_{ave18})] \qquad (2a)$$

where P_{18} is the average PAR (μmol m^{-2} s^{-1}) over the past 18 hours and T_{18} is the average ambient air temperature (deg C) over this time period. PT_{ave18} is the average value for the season. This would be appropriate if we had emission factors that were based on the emission rates that are representative of PT_{ave18}. Instead, we use emission factors that are representative of unknown conditions. Since the objective of this exercise is to consider high temperatures during conditions of fairly constant sunny conditions (i.e., hot sunny periods), and in order to compare with the other methods, we should eliminate the PAR variable from this equation. Also, the algorithm was based only on data collected at one time of day (1300) so it is uncertain how well it will work throughout the day. If we assume the same normalizing antecedent temperature as Guenther et al. then the appropriate equation is

$$\gamma_T = \gamma_{T1} [1 + 0.04 (T_{18} - 301)] \qquad (2b)$$

As was the case with the Geron et al. method, Sharkey recommends a method using both temperature and PAR that we will reduce to temperature only (for the reasons described above). Sharkey et al. (2000) do not present their data in a manner that can easily be used for regional emission modeling but we can approximate their observed temperature sensitivity is an increase of about 6% per C^{-1}. We can thus calculate the antecedent temperature activity factor as

$$\gamma_T = \gamma_{T1} [1 + 0.06 (T_{48} - 301)] \qquad (3)$$

where T_{48} is the average ambient air temperature (K) over the past 48 hours and γ_{T1} is the activity factor accounting for the temperature of the past hour (e.g., as calculated by Guenther et al. 1993).

$$\gamma_T = \gamma_{T1} [1+0.04 (T_{18} - 301)+0.02 (T_{48} - 301))+0.14 (T_{360} - 301)] \qquad (4)$$

Each method requires estimating a different parameter and a new input data file should be generated for each of these long-term average temperatures. The inputs for equation 1 and 3

could consist of one value (per grid) per day while the value used for equation 2 should be updated hourly.

Along with algorithms describing the relationship between prolonged leaf temperatures and isoprene emissions, a necessary component of characterizing the influence of drought on these emissions is a method for estimating accurate leaf temperature. The original BEIS model included methods for calculating leaf temperature by characterizing leaf energy balance. The second version, BEIS2, dropped these routines and just assumed that leaf temperature was equal to ambient temperature. This was not because it was assumed that the difference between leaf and ambient temperature was insignificant but was due to a recognition that the BEIS methods were not reliable and probably did not result in more accurate estimates of leaf temperature. Accurate estimates of leaf temperature are likely to be important under many conditions but are particularly important under drought conditions. Any attempts to model isoprene emissions during drought should include efforts to model isoprene emissions during drought conditions. An example of model routines that can be used to model leaf temperature are those applied by Guenther et al. 1999 which are based primarily on the work of Goudrian and Van Laar (1994) and Leuning et al. (1995). Both the original BEIS leaf temperature method and the model of Guenther et al. (1999) could be used for the purpose of testing the sensitivity of model results to leaf temperature calculations. These routines can be implemented relatively easily. However, more complex land surface models are needed in order to characterize soil moisture and its impact on stomatal conductance as is discussed below.

II. Water limitations

The three general alternatives for characterizing the impact of water limitations on VOC emissions are to use 1) drought indices based on hydrological balance estimates, 2) an index based on remote sensing measurements of vegetation condition and/or temperature, or 3) leaf water potential calculated using a land surface model. Each method has advantages and disadvantages in terms of effort, current availability, demonstrated reliability and potential accuracy.

Hydrological based drought indices are straightforward methods that have been evaluated extensively and are used by government agencies for a variety of purposes such as determining whether to grant emergency drought assistance. These indices assimilate available rainfall, snowpack, streamflow, irrigation, and temperature data and, in some cases, model evapotranspiration, ground water, reservoir storage and other hydrological fluxes. The Palmer Drought Severity Index (PDSI) is an example of an index that is frequently used although there are several other possibilities. Weekly PDSI values are available throughout the growing season for each U.S. Climate Division in the archive accessed at http://nic.fb4.noaa.gov/products/analysis_monitoring. Given the limited understanding of the impact of water limitations on biogenic VOC emission, a simple relationship between this index and a emission activity factor associated with water limitations (γ_w) should be used until more observations are available:

$$\gamma_w = 1, \qquad PDSI > DI_{min} \qquad (5a)$$

$$\gamma_w = 1 + (PDSI - DI_{min}) / (DI_{min} - DI_{max}) \quad DI_{min} > PDSI > DI_{max} \qquad (5b)$$

$$\gamma_w = 0, \quad PDSI < DI_{max} \qquad (5c)$$

where DI_{min} and DI_{max} are empirical parameters that indicate the PDSI at which emissions begin to increase and the PDSI at which emission are negligible. For example, a reasonable choice would be to set DI_{min} =-2 and DI_{max} = -4 which would cause emissions to begin to decrease with a moderate drought and become negligible for an extreme drought.

A promising method for high-resolution characterization of plant water availability involves the use of remote sensing. For example, the University of Montana has been producing and archiving (give web site) a near real-time surface moisture index (SMI) that characterized surface moisture conditions. The SMI incorporates vegetation status through the use of Normalized Difference Vegetation Index (NDVI) and satellite derived surface temperature. The method assumes that surface moisture is related to the slope of the regression between NDVI and surface temperature. Evaluations of the method are currently underway by the University of Montana. However, a preliminary screening of the archive indicates that their SMI maps do not capture the east Texas drought of August-September 2000. It is likely that some tuning of the procedure is needed in order to better characterize plant water limitations in Texas. In the event that a suitable modified algorithm is obtained, then the impact on emissions could be estimated in a manner similar to equation 5.

It is desirable to relate biogenic emissions to measurable physiological parameters that control emission variations. Leaf water potential is the most likely candidate for describing the role of water limitations on biogenic emissions from leaves. This parameter also may be needed for estimating accurate leaf temperatures during drought conditions. There are several land surface models (LSMs) that can be used to calculate water potential. There have been a number of evaluations of the various models but no single model stands out as outperforming all others. This is not surprising since the various models tend to borrow heavily from each other and differences are primarily associated with the different primary tasks of the models. A key aspect of any LSM application is that the model may need to be parameterized for Texas soils and vegetation. A good choice of an LSM is one that is intended for use in a meteorological model that will be used for the air quality model simulations for which biogenic emissions are desired. These interactions could be done in an off-line mode although it would ultimately be desirable to have them in a coupled model. For example, if the NCAR/PSU MM5 model (WARF) is being used to generate meteorological conditions for the air quality simulation then the LSM in this model should be used as the basis for estimating leaf water potential. Given the lack of observational data, leaf water potential would currently have to be related to biogenic VOC emissions using a simple function similar to equation 5.

III. Leaf area

Drought conditions can also impact biogenic VOC emissions by reducing the leaf area available for emissions. The reduction in foliage can readily be incorporated into GLOBEIS 2.2 by providing procedures to input relative leaf area. The model currently uses a static database based on monthly averages for several years of NDVI data. Ten day NDVI composites could

instead be provided to the model as an additional data input file. Space based sensors (AVHRR for pre 2000 and MODIS for later periods) can provide the needed NDVI composites. In some cases, higher resolution observations may be available from aircraft flights.

Task 2. Scoping study for long-term biogenic emissions flux project

The purpose of this task is to develop several feasible researches plans for investigating biogenic emission fluxes in southeastern Texas. The overall objectives of the planned research are to improve and evaluate biogenic emission models for this region. The specific questions that would be addressed by this research include the following:

1. What are the basal emission factors for Texas tree species? How do these species' emission rates react to environmental changes (temperature, PAR, soil moisture, extended drought)? Which chemicals are emitted from Texas trees in the greatest quantities? If current models do not accurately simulate the observed behavior then what adjustments should be made to enable accurate simulation of these observations?

2. How does the emission behavior of Texas trees vary with season, including periods of drought? How much interannual variation is observed? If current models do not accurately simulate the observed behavior then what adjustments should be made to enable accurate simulation of these observations?

3. Are the current biogenics models suitable for accurately estimating biogenic emissions from major southeastern Texas forests, shrublands, and suburban regions? If current models do not accurately simulate the observed behavior then what adjustments should be made to enable accurate simulation of these observations?

4. Does deposition of biogenic emissions play a large role in the net landscape-level flux? What are the deposition rates of the oxidation products of biogenic emissions? What are the deposition rates of NOx and ozone to important southeast Texas landscapes? If current models do not accurately simulate the observed behavior then what adjustments should be made to enable accurate simulation of these observations?

There are a variety of complementary tools that have been developed or improved in the past decade that can be utilized to address the above questions. In some cases, there are several alternative and decisions must be made according to technical feasibility, accuracy, and cost. The potential tools for addressing each major research area are described below.

<u>Emission factors and emission mechanisms: Investigating the processes controlling emission variations and characterizing species level emission factors.</u>

Enclosure measurement systems are extremely useful for investigating the mechanisms controlling biogenic fluxes and for quantifying emission factors for individual plant species. Both the emission factors and the emission algorithms used on current emission models are

primarily based on the results of enclosure studies. These studies can be accomplished either in laboratory of field settings. Laboratory studies have the advantage of greater capabilities for environmental control and lower cost. The major disadvantage is that potted plants do not always behave as they would in a natural environment. Therefore the best enclosure measurement strategy is to begin with laboratory studies to gain a general understanding of an issue and then use limited field measurements to verify these results. Additional choices that must be made are the type of enclosure that will be used and the analytical system that will be utilized. Although simple and inexpensive enclosure systems are useful for some studies, systems that provide environmental control (the ability to control at least leaf temperature and light) and measure photosynthesis and stomatal conductance have significant advantage (but are, of course, considerably more expensive).

Two enclosure studies should be considered as part of any Texas biogenic VOC emissions research program: an investigation of the influence of drought on isoprene emissions and a study of emission factors for important Texas vegetation. The drought study should begin in a laboratory setting using an automated, multi-cuvette, environmental control chamber with continuous measurements of photosynthesis, stomatal conductance and transpiration (by an infra-red gas analyzer) and continuous isoprene analysis by chemiluminescence analyzer or proton transfer reaction mass spectrometry. Water potential would be measured daily. Three species of important Texas trees should be selected for investigation. An experimental and control plant for each species would be used for each experiment and the experiment would be repeated. The studies would be designed to relate isoprene emissions to water potential by decreasing water potential (by decreasing the amount of water given to the plant) to the point that isoprene emissions begin to decrease and then determining the relationship between additional changes in water potential and isoprene emission. The results of the laboratory study would then be evaluated at a Texas field site using a portable environmental control cuvette (with photosynthesis and stomatal conductance measurements) and isoprene analysis using a portable leaf cuvette and GC-PID. Two field campaigns would be conducted: one when drought is not expected and one when drought is expected.

A second study would focus on expanding the existing database of biogenic VOC emission factors for Texas vegetation and the development and evaluation of emission activity factors. Initial studies would be conducted with greenhouse grown plants with analysis by PTR-MS to characterize a wide range of VOC (isoprene, total monoterpenes, acetone, methanol, acetaldehyde, etc.). Thirty important Texas plant species would be investigated to determine their emission factors as well as their response to changes in light and temperature. The isoprene emission results from these laboratory studies would be evaluated by a field campaign investigating the emission factors and emission activity behavior of six important Texas trees. The isoprene emission rates of four individuals of each species would be measured over a range of light and temperature conditions using an environmentally controlled portable leaf cuvette and a portable GC-PID.

<u>Temporal variations: Tools for investigating (and evaluating model simulations of) diurnal, seasonal and interannual variations in fluxes.</u>

Adding measurements of reactive trace gases to a facility dedicated to long term flux measurements (typically CO2) is relatively inexpensive compared to the cost and effort of setting up a new facility. Surprisingly, there are currently no Texas sites listed in the AMERIFLUX program, which is a network of about 40 long term eddy flux sites. A lower cost, temporary facility can be set up for an experiment lasting several weeks but this will not be useful for characterizing phenomena such as drought induced flux variation. If a more permanent facility is set up then the study should continue throughout one growing season (April-October). A longer-term study of two to three years should attempt year round measurements.

A lower cost experiment investigating isoprene emission variations over one growing season could be accomplished by eddy covariance using a chemiluminescence isoprene analyzer with the method described by Guenther and Hills (1998). Eddy covariance measurements of CO2 and sensible and latent heat fluxes should accompany any biogneic VOC emission studies and can be accomplished using a sonic anemometer and an infrared gas analyzer. With additional funds, a longer-term study of two to three years could investigate variations of a wide range of VOC emissions (isoprene, total monoterpenes, acetone, methanol, acetaldehyde, etc.) and deposition (e.g., methacrolein and MVK) using eddy covariance and PTR-MS as described by Karl et al. (2000). Fluxes of different compounds should be obtained for each 30-minute period using the disjunct sampling technique described by Rinne et al. (2000, 2001). A final addition would include ozone and NO, NO2 fluxes. Fluxes of these compounds have been measured by continuos eddy covariance but it recommended that slower response instruments, which are more stable and less expensive, be used along with a disjunct eddy sampling system (e.g., Rinne et al. 2000, 2001). Alternatives to eddy covariance include relaxed eddy accumulation and gradient methods. While these methods are attractive for short-term studies due to their lower set up costs, they are not recommended for longer-term studies.

Site selection…

<u>Regional Studies: Tools for investigating (and evaluating model simulations) of regional variations in fluxes.</u>

A lack of tools for measuring biogenic emissions on the scales used in regional air quality models has been a significant gap in our ability to characterize and evaluate biogenic emission models. This gap is closing with the development of aircraft borne systems for eddy flux measurements of reactive trace gases (e.g., Greenberg et al. 1999). Efforts to extend these capabilities are currently underway at the National Center for Atmospheric Research (NCAR) and other institutions. Possibilities for aircraft flux measurements include eddy covariance measurements using PTR-MS on an existing flux aircraft, such as those maintained by the National Science Foundation, or using disjunct eddy accumulation (e.g., Rinne et al. 2000) with a portable wind probe and a rented light aircraft (this has been used for CO2 fluxes and NCAR is currently working on using this method for VOC). The costs of deploying the NSF aircraft would be paid by NSF if the experiment falls within the NSF program plan and the cost of operating a light aircraft are very reasonable so either of these options can be accomplished at reasonable cost. Each aircraft campaign would characterize average emissions over a scale of about 10-15 km for the three or four landcover types (e.g., oak forest, oak/pine savanna, suburbs)

within a region to which air quality simulations are most sensitive. Multiple aircraft campaigns could investigate multiple regions (e.g., Houston, Dallas, etc.)

An alternative to aircraft investigations of regional distributions of emission capacities would be a series of tower flux studies. The effort involved in characterizing a large number of landscapes would be greater for the tower studies than the aircraft studies and the measurements would be less representative (because the aircraft flux measurements would integrate over a larger area. However, an advantage of this approach is that some information on diurnal and day-to-day variations would be obtained. This option is also technically easier than the aircraft method and would be the only option if an aircraft system were unavailable.

Chemistry, transport and emissions: Tools for investigating (and evaluating model simulations) of regional variations in fluxes, chemistry and transport

In addition to direct measurements of trace gas fluxes, a recommended component of the research program is the use of tethered balloon sampling systems for characterizing vertical profiles ozone, VOC, particles, CO2, winds, and boundary layer height. The tethered balloon observations would be used to evaluate the combined processes of chemistry, transport and emissions in air quality simulation models. Each tethered balloon campaign would characterize average emissions over a scale of about 10-15 km for the three or four landcover types (e.g., oak forest, oak/pine savanna, suburbs) within a region to which air quality simulations are most sensitive. Multiple aircraft campaigns could investigate multiple regions (e.g., Houston, Dallas, etc.).

Research program scenarios

The costs associated with the following scenarios do not include equipment purchase, instrument development or the training of personnel. They are reasonable costs for institutions that already have the necessary tools and expertise available and are able to provide some cost sharing. For other institutions, the cost is likely about 50% higher.

1000K (4 years)
1. 36 month tower study: eddy flux measurements of all major VOC, CO_2, H_2O, O_3, NO_x
2. Enclosure studies: Drought study, emission factor and light/temp. dependence survey
3. Tethered balloon studies: 2 regions
4. Aircraft studies: 2 regions

930K (4 years)
1. 36 month tower study: eddy flux measurements of all major VOC, CO_2, H_2O
2. Enclosure studies: Drought study, emission factor and light/temperature dependence survey
3. Tethered balloon studies: 2 regions
4. Aircraft studies: 2 regions

810K (4 years)
1. 24 month tower study: eddy flux measurements of all major VOC, CO_2, H_2O
2. Enclosure studies: Drought study, emission factor and light/temperature dependence survey

3. Tethered balloon studies: 2 regions
4. Aircraft studies: 2 regions

700K (3-4 years)
1. 24 month tower study: eddy flux measurements of all major VOC, CO_2, H_2O
2. Enclosure studies: Drought study, emission factor and light/temperature dependence survey
3. Tethered balloon studies: 2 regions
4. Aircraft studies: 1 region

610K (3-4 years)
1. 24 month tower study: eddy flux measurements of all major VOC, CO_2, H_2O
2. Enclosure studies: Drought study, emission factor and light/temperature dependence survey
3. Tethered balloon studies: 1 region
4. Aircraft studies: 1 region

520K (2-3 years)
1. 24 month tower study: eddy flux measurements of all major VOC, CO_2, H_2O
2. Enclosure studies: Drought study, emission factor and light/temperature dependence survey
3. Aircraft studies: 1 region

410K (2-3 years)
1. 24 month tower study: eddy flux measurements of all major VOC, CO_2, H_2O
2. Enclosure studies: Drought study, emission factor and light/temperature dependence survey

390K (2 years)
1. 6 month tower study: eddy flux measurements of isoprene, CO_2, H_2O
2. Enclosure studies: Drought study, emission factor and light/temperature dependence survey
3. Aircraft study: 1 region

280K (1-2 years)
1. 6 month tower study: eddy flux measurements of isoprene, CO_2, H_2O
2. Enclosure studies: Drought study, emission factor and light/temperature dependence survey

150K (1 year)
1. Enclosure studies: Drought study, emission factor and light/temperature dependence survey

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