Insights into the dynamics of forest succession and non-methane hydrocarbon trace gas emissions

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Abstract. Natural biogenic non-methane hydrocarbon (NMHC) emissions significantly influence the concentrations of free hydroxyl and peroxy radicals, carbon monoxide and tropospheric ozone. Present concerns with air pollution and the global carbon balance call for a better understanding of the respective roles of climate dynamics and vegetation succession in determining NMHC emissions. This constitutes the focus of the present paper. The approach consists in coupling the Energy, Water and Momentum Exchange and Ecological Dynamics model, a climatically sensitive, physically based gap phase forest dynamics model, and NMHC trace gas emission algorithms to assess possible changes in NMHC emissions from forests under stationary and changing climatic conditions. In summary, it is possible to follow the temporal evolution of foliar emissions over centuries using a vegetation dynamics model coupled with an NMHC emissions module.

INTRODUCTION

Natural biogenic non-methane hydrocarbon (NMHC) emissions influence the concentrations of free hydroxyl and peroxy radicals, carbon monoxide (Zimmerman et al., 1978; Chameides & Cicerone, 1978; Logan et al., 1981) and tropospheric ozone (Crutzen, 1974), a strong oxidant and a radiatively active trace gas. The oxidation of foliar emissions of terpenes and isoprenes could contribute annually from 14% to possibly 88% of the total flux of CO into the atmosphere (Zimmerman et al., 1978). Foliar emissions also constitute a small but significant flux of 0.8 Pg(C)yr⁻¹ to the atmosphere (Warneck, 1988), compared to the 7 Pg(C)yr⁻¹ due to fossil fuel burning, cement manufacturing and forest clearing (Brown et al., 1994), and may represent a significant contribution of organic acids in rural and urban areas (Lamb et al., 1987). Finally, it should be noted that vegetation is the dominant source of such natural hydrocarbons (Zimmerman et al., 1978).

This short paper describes preliminary insights gained with EXE, the Energy, Water, and Momentum Exchange and Ecological Dynamics model (Martin, 1990; 1992), in combination with non-methane hydrocarbon (NMHC) trace gas emission algorithms to assess possible changes in NMHC emissions from forests under stationary and changing climatic conditions.

SIMULATING FOREST SUCCESSION AND LAND–SURFACE DYNAMICS

A brief description of EXE

The Energy, Water, and Momentum Exchange and Ecological Dynamics model couples a physically and physiologically based water budget with an explicit treatment of ecological dynamics. In principle, EXE could be forced by atmospheric general circulation model output. EXE is made of two modules, ecological and physical. LINKAGES (Pastor & Post, 1984; 1986) provided the basis for the ecological module. Significant changes were made to couple physiology to physics in an effort to make the model realistically climatically sensitive. The physical module was built from scratch. It treats water uptake by the roots from the soil and atmospheric demand for water vapour explicitly. The forest hydrology and microclimate is computed once at daytime and once at night-time for the 365 days of the year. Information regarding the hydrology and the microclimate is transferred to the ecological module; the development of...
TABLE 1. GCM climate change scenarios.

| GCM  | J   | F   | M   | A   | M   | J   | J   | A   | S   | O   | N   | D   |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| St. Paul, MN (45°N, 93°W) temperature changes (°C) |     |     |     |     |     |     |     |     |     |     |     |
| GFDL | 5.6 | 6.2 | 6.6 | 5.5 | 3.4 | 9.3 | 9.2 | 7.5 | 7.2 | 6.3 | 6.3 | 7.1 |
| GISS | 5.1 | 5.8 | 5.1 | 5.2 | 2.4 | 3.6 | 2.1 | 3.5 | 6.5 | 3.7 | 6.1 | 5.7 |
| OSU  | 5.4 | 3.8 | 4.3 | 2.6 | 3.4 | 4.5 | 3.5 | 4.2 | 3.5 | 2.6 | 2.3 | 2.9 |
| UKMO | 10.0| 10.3| 9.0 | 9.3 | 7.0 | 6.3 | 7.3 | 10.7| 8.8 | 7.1 | 9.1 | 10.9|
| St. Paul, MN (45°N, 93°W) precipitation changes (mm) |     |     |     |     |     |     |     |     |     |     |     |
| GFDL | 129.0| 116.0| 109.0| 96.0| 103.0| 63.0| 73.0| 76.0| 89.0| 83.0| 119.0| 119.0|
| GISS | 116.0| 103.0| 130.0| 106.0| 106.0| 103.0| 106.0| 76.0| 96.0| 113.0| 119.0| 119.0|
| OSU  | 123.0| 129.0| 113.0| 89.0| 76.0| 89.0| 106.0| 96.0| 113.0| 139.0| 109.0| 89.0 |
| UKMO | 126.0| 116.0| 126.0| 123.0| 133.0| 123.0| 86.0| 96.0| 93.0| 109.0| 123.0|     |
| Duluth, MN (47°N, 92°W) temperature changes (°C) |     |     |     |     |     |     |     |     |     |     |     |
| GFDL | 6.5 | 7.5 | 7.6 | 6.3 | 3.6 | 9.4 | 9.4 | 7.9 | 7.4 | 6.8 | 6.4 | 7.5 |
| GISS | 5.1 | 6.0 | 4.9 | 5.2 | 2.0 | 3.7 | 2.2 | 3.1 | 5.5 | 3.7 | 6.0 | 5.1 |
| OSU  | 5.1 | 3.9 | 4.3 | 2.5 | 3.5 | 4.2 | 4.1 | 3.3 | 2.6 | 2.5 | 2.7 |     |
| UKMO | 9.7 | 10.9| 10.7| 10.9| 7.9 | 6.5 | 7.1 | 8.8 | 8.3 | 7.4 | 9.6 | 11.1|
| Duluth, MN (47°N, 92°W) precipitation changes (mm) |     |     |     |     |     |     |     |     |     |     |     |
| GFDL | 123.0| 109.0| 119.0| 83.0| 96.0| 69.0| 76.0| 76.0| 86.0| 86.0| 116.0| 126.0|
| GISS | 103.0| 106.0| 119.0| 109.0| 96.0| 116.0| 99.0| 116.0| 130.0| 109.0| 116.0| 130.0|
| OSU  | 129.0| 129.0| 116.0| 86.0| 83.0| 93.0| 113.0| 93.0| 113.0| 143.0| 116.0| 89.0 |
| UKMO | 126.0| 123.0| 126.0| 136.0| 136.0| 126.0| 96.0| 83.0| 106.0| 89.0| 109.0| 123.0|

The forest is then simulated. This results in new physical and physiological characteristics of the forest. At this point, the cycle can repeat itself.

**Input data, run specifications and computer requirements**

Forest succession under 400 years of present climatic conditions are simulated, then numerical experiments to examine the sensitivity of model forests to climatic changes are performed using scenarios generated with the Geophysical Fluid Dynamics Laboratory (GFDL; Wetherald & Manabe, 1986; Manabe & Wetherald, 1987), the Goddard Institute for Space Studies (GISS; Hansen et al., 1983), the Oregon State University (OSU; Schlesinger & Zhao, 1989), and the United Kingdom Meteorological Office (UKMO; Mitchell, 1983; Wilson & Mitchell, 1987) atmospheric general circulation models (GCMs). The changes in precipitation and temperature are displayed in Table 1.

The climate change scenarios only include monthly temperature and precipitation data. The perturbed climate is constructed by applying absolute changes to present-day climatology. Each altered temperature is computed as the sum of the daily temperature value and the absolute monthly change for that month. Altered precipitation is also computed on the basis of present-day conditions. It was assumed that the temporal distribution of rain remains the same, but that amounts on a given day changed. Hence, the change in precipitation expected from climate change in
that month is added to each rainy day in the present climate. Radiation is held identical to present-day conditions, as well as wind velocity. Humidity can be assumed either to behave so that specific humidity remains constant (the number of water molecules in a parcel of air does not change) or that relative humidity stays the same (the number of water molecules changes with temperature). Since no drought stress is experienced in the simulations with the fixed humidity case, the fixed humidity case is not simulated.

Simulating forest dynamics with EXE on one plot for 500 years takes about 1 hour of IBM RISC 6000/580 CPU time. EXE therefore ran for a total of approximately 160 hours (= 20 plots per simulation x 2 sites x 4 scenarios per site x 1 hour per 500 year simulation) to complete this sensitivity analysis exercise.

**CALCULATING NON-METHANE HYDROCARBON EMISSION FROM FORESTS**

**Input date**

Biogenic NMHC emissions are a function of the foliar mass of the tree species present (Zimmerman et al., 1978).

**TABLE 2. Standardized NMHC fluxes for twenty-nine tree genera.**

| i | Genus                          | Isoprene $a_{i1}$ | Terpene $a_{i2}$ |
|---|--------------------------------|-------------------|------------------|
| 1 | Fir (Abies)                    | 0.0               | 3.0              |
| 2 | Maple (Acer)                   | 0.0               | 3.0              |
| 3 | Birch (Betula)                 | 0.0               | 0.2              |
| 4 | Hickory (Carya)                | 0.0               | 1.6              |
| 5 | American chestnut (Castanea dentata) | 0.0 | 0.6 |
| 6 | Sugarberry (Cellis laevigata)   | 0.0               | 0.2              |
| 7 | Flowering dogwood (Cormus florida) | 0.0 | 1.6 |
| 8 | American beech (Fagus grandifolia) | 0.0 | 0.6 |
| 9 | Ash (Fraxinus)                 | 0.0               | 0.0              |
| 10 | Plum and cherry (Prunus)       | 0.0               | 0.0              |
| 11 | Walnut and butternut (Juglans) | 0.0               | 3.0              |
| 12 | Eastern red cedar (Juniperus virginiana) | 0.0 | 0.6 |
| 13 | Sweetgum (Liquidambar styrciflua) | 70.0 | 3.0 |
| 14 | Yellow poplar (Liriodendron tulipifera) | 0.0 | 0.2 |
| 15 | American hornbeam (Carpinus caroliniana) | 0.0 | 1.6 |
| 16 | Spruce (Picea)                 | 14.0              | 3.0              |
| 17 | Pine (Pinus)                   | 0.0               | 3.0              |
| 18 | Sycamore (Platanus occidentalis) | 35.0 | 0.0 |
| 19 | White oak (Quercus alba)       | 70.0              | 0.2              |
| 20 | Red oak (Quercus rubra)        | 70.0              | 0.2              |
| 21 | Basswood (Tilia)               | 0.0               | 0.6              |
| 22 | Eastern hemlock (Tsuga canadensis) | 0.0 | 0.2 |
| 23 | Elm (Ulmus)                    | 0.0               | 0.0              |
| 24 | Yellow buckeye (Aesculus octandra) | 0.0 | 0.6 |
| 25 | Tamarak (Larix laricina)       | 0.0               | 1.6              |
| 26 | Aspen and poplar (Populus)     | 70.0              | 0.0              |
| 27 | Northern white cedar (Thuja occidentalis) | 0.0 | 0.6 |
| 28 | Black tulepo (Nyssa sylvanica)  | 14.0              | 0.6              |
| 29 | Eastern hop hornbeam (Ostrya virginiana) | 0.0 | 0.6 |

The emission rates are in $\mu$(g) g$^{-1}$ (dry weight foliar mass) h$^{-1}$. They represent emissions from leaves for a temperature of 30°C and a photosynthetically active radiation flux of 1000 $\mu$mol m$^{-2}$ s$^{-1}$ (source: Guenther, Zimmerman & Wildermuth, 1994). To account for canopy light interception, these numbers are divided by 1.75 in the calculations.

NMHC emission algorithms

From the regressions presented in Lamb et al. (1987), the hourly NMHC emission rate by genus and by emission type in $\mu$(g)(C)g$^{-1}$ (dry weight foliar mass) h$^{-1}$, can be expressed as

$$e_{i,j}(T) = a_{i,j}10^{b_{j}(T-30)},$$

where $i$ refers to the genus (see Table 2 for the twenty-nine tree genera considered); $j$ refers to the emission type ($j = 1$ for isoprene and $j = 2$ for terpene); $T$ is temperature, in °C; $a_{i,j}$ is the emission rate for genus $i$ and emission type $j$, standardized at 30°C (values for $a_{i,j}$ may be found in Table 2); and $b_{j}$ is a constant characteristic of the change in irradiance and canopy temperature (Lamb et al., 1987). As summarized in Fig. 1, the EXE output data used as input in the NMHC trace gas emission calculations are daytime and night-time canopy temperatures averaged over twenty forest plots of one-twelfth of hectare each, live leaf biomass by genus averaged over the twenty forest plots, day length and the dates for the beginning and end of the growing season as computed by EXE.
emission type \( j \) with temperature. \( b_1 = 0.0415 \) (isoprene) and \( b_2 = 0.0172 \) (terpene) (Lamb et al., 1987).

Emission rates by genus and by emission type on a daily basis are computed as

\[
E_{i,j,k}(T_k^{\text{daytime}}, T_k^{\text{night-time}}) = 24 [b_{i,j}T_k^{\text{daytime}} + (1 - f_k)\delta_{i,j}T_k^{\text{night-time}}].
\]

where \( k \) is the Julian day; \( T_k^{\text{daytime}} \) is the daytime temperature, in °C; \( T_k^{\text{night-time}} \) is the night-time temperature, in °C; \( f_k \) is the fraction of the day during which there is light; and \( \delta \) is zero for isoprene at night-time and one otherwise.

Yearly emissions by NMHC emission type, in \( \mu g(C)g^{-1}(\text{dry weight foliar mass})^{-1} \), are calculated as

\[
F_i = \sum_{k=1}^{365} \sum_{j=1}^{30} r_i B_i E_{i,j,k}
\]

where \( r_i \) is the ratio of dry weight foliar mass to live weight foliar mass for genus \( i \) and \( B_i \) is the live weight foliar mass for genus \( i \).

**NMHC EMISSIONS FROM FORESTS OVER CENTURIES UNDER STATIONARY AND PERTURBED CLIMATIC CONDITIONS**

Secondary succession as simulated by EXI starts with an empty area which is progressively invaded by so-called
pioneer species. After having reached maturity, these pioneer species are progressively replaced, in general, by other species. After about 400–500 years, in the northern temperate/boreal forest transition zone chosen for the simulation, a relatively stable vegetation assemblage is attained which can maintain itself for long periods of time. At this point in the simulation, the climate change scenarios are used to evaluate the effects of climatic perturbations on stable mature forests.

**St Paul, MN area**

In the St Paul, MN region, by year 400, NES produces the maple–basswood (*Acer–Tilia*) forest most typical of the area with an early abundance of aspen (*Populus grandidentata, P. tremuloides*) and yellow birch (*Betula alleghaniensis*).

Between year 400 and year 500, the climate change scenarios are used. Although not always at the same time, the biomass of the dominant maple decreases in all cases. Under stationary climatic conditions, as shown in Figs 2, 3, 4 and 5, isoprene emissions are significantly greater than the terpene emissions during the first 160 years of the simulation. At this point, terpenes start dominating the signal. This result is explained by the early dominance of aspen which, with a standardized rate of 70 µg(C)g⁻¹(dry weight foliar mass) h⁻¹, is a high isoprene emitter. The later high rates of terpene emissions are explained by the late...
successional dominance of maple which, with a standardized rate of $3 \mu g(C)g^{-1}(dry \ weight \ foliar \ mass) h^{-1}$, is a high terpene emitter.

As climate change takes place, it was pointed out that biomass of this mature maple forest decreases. This is more than compensated by the rise in temperature which leads to a steep increase in terpene emissions with each of the GCM scenarios used.

**Duluth, MN area**

In the Duluth, MN area, the abundance of aspen (*Populus grandidentata, P. tremuloides*) during the first 150 years of the simulation is very high. By year 400, the forest is dominated by a spruce (*Picea glauca, P. mariana*) forest with some yellow birch in the understory.

The dominant spruce die back and are replaced by maple between year 400 and year 500. The timing of the disappearance of the spruce and the appearance of a (young) maple-dominated forest depends entirely on the GCM scenario used.

The first comment to make regarding the simulation on the Duluth site is that, as can be seen in Figs 6, 7, 8 and 9, NMHC emissions are higher than on those on the St Paul site by one order of magnitude. The results obtained for the Duluth area are also different from those for the St Paul area in that, during the 500 years of the whole simulation, isoprene and terpene emissions have the same order of magnitude, with terpene emissions being slightly higher than isoprene emissions after the first 100 years.

As previously pointed out, between year 400 and 500, spruce disappears and is replaced by maple as climate change takes place. Although the exact timing of this switch is a function of the GCM climate change scenario used, similar patterns emerge. The spruce produces isoprene at a standardized rate of $14 \mu g(C)g^{-1}(dry \ weight \ foliar \ mass) h^{-1}$ and terpenes at a rate of $3 \mu g(C)g^{-1}(dry \ weight \ foliar \ mass) h^{-1}$, while maple produces no isoprene and emits terpenes at a standardized rate of $3 \mu g(C)g^{-1}(dry \ weight \ foliar \ mass) h^{-1}$. Therefore, despite the emission enhancement effect of temperature, the relatively low NMHC emission rate of the maple and the low leaf biomass of the young maples explain a very sharp reduction in total NMHC emissions.

**DISCUSSION AND CONCLUSION**

These preliminary results show that it is possible to follow the temporal evolution of NMHC trace gas emissions under stationary and perturbed climatic conditions over timescales of centuries to millennia using climatically sensitive, physically based gap dynamics forest models such as EXE coupled with NMHC trace gas emissions algorithms.

The results of the simulations presented here indicate that significant changes in isoprene and terpene emissions can occur both as vegetation succession takes place under stationary climatic conditions and as climatic changes come about. These results, moreover, point out that emissions may either decrease or increase depending on the forest microclimate and the successional stage of the vegetation on the site. Recent formulations of biogenic NMHC emissions make the emission rate light-dependent (cf. Guenther et al., 1993). In the present simulations, a simple temperature-based algorithm was used. Although this simplification significantly affects quantitative estimates of yearly emissions at the continental scale, it should minimally alter the qualitative patterns of biogenic NMHC emissions described here.

Because of the synergistic interaction of changes in species absolute and relative abundance, and changes in temperature, the impact of global change on NMHC emissions rates is difficult to predict. Nevertheless, coupled models of the kind described here may provide useful insights into the possible direction of such changes.

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