Footprint climatology estimation of potential control ring contamination at the Duke Forest FACTS-1 experiment site

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Abstract

Long-term airport weather observations, calibrated by on-site measurements, were used to create a footprint climatology for the Forest Atmosphere Carbon Dioxide Transfer and Storage-1 (FACTS-1) site in the Duke Forest, NC. The footprint was centered over each 30-m diameter control ring to estimate potential contamination from four CO\textsubscript{2}-enriched rings at the site. The footprint partitions the upward fluxing CO\textsubscript{2} at any canopy-top point into relative contributions from grids in the surrounding forest. Additional footprints were generated for taller forest heights to estimate potential contamination levels at the site as the forest grows. The results showed a small percentage of flux originating from enriched areas of the site reaching the control rings. The ring with the highest contamination received 1\% of its total scalar flux from enriched areas. As the forest grows, the absolute contribution from the enriched rings will increase slightly, but the proportional contribution will decrease with time due to increases in canopy roughness and a larger footprint (greater fetch) during stable conditions. ©2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Brookhaven National Laboratory (BNL), Duke University, and the US Department of Energy, Office of Health and Environmental Research have jointly developed the Forest Atmosphere Carbon Dioxide Transfer and Storage-1 (FACTS-1) facility in the Duke Forest. This project was designed to be part of a worldwide network of Free Air–Carbon Dioxide Enrichment (FACE) sites, each operating in a unique climate and vegetation classification. These sites were constructed to study the long-term effects of increased CO\textsubscript{2} on ecosystems and to quantify the effects of increased CO\textsubscript{2} levels in the atmosphere. Initial results have been reported in Idso and Idso (1994), Kimball et al. (1994) and Ellsworth et al. (1995). The FACTS-1 site was designed to combine this objective with the ability to study the CO\textsubscript{2} exchange processes within the forest.
The FACTS-1 site started with a 30-m diameter prototype ring built within a 9 m tall uniform, regenerating loblolly pine plantation (Katul et al., 1996; Hendrey et al., 1998) in the Duke Forest. Six more rings have since been added to the site to account for variations due to soil type. The air within three of these new rings is maintained at 200 μmol CO$_2$ per mole of air greater than ambient CO$_2$, like the prototype, while the other three are controls and are not CO$_2$ enriched.

Pasquill (1972) was the first to consider an upwind source distribution as contributing to the properties measured at an elevated point. This concept has been advanced through ‘footprint’ models created to estimate the upwind, spatial distribution of sources based on local meteorological conditions (Schuepp et al., 1990; Leclerc and Thurtell, 1990; Schmid and Oke, 1990; Wilson and Swaters, 1991; Horst and Weil, 1992, 1994; Schmid, 1994; Flesch et al., 1995; Flesch, 1996; Leclerc et al., 1997; Schmid, 1997; Amiro, 1998). Recently, footprint models have been used to estimate the fluxes of evapotranspiration (Amiro, 1998) and tracer elements (Finn et al., 1996). The term ‘footprint climatology’ has been defined as a long-term estimation of the source contributions at a site (Amiro, 1998). The objective of this study was to develop a footprint climatology at the FACTS-1 site based on 25 years of data and to use it to estimate potential control ring contamination emanating from the CO$_2$ enriched areas.

2. Methods

2.1. General approach

In this study, the upward fluxing CO$_2$ at any canopy-top point in the $x$–$y$ plane was partitioned into the spatial distribution of underlying sources contributing to it. This spatial distribution of relative contribution was the ‘footprint’. Since the forest canopy is considered uniform, the climatological average footprint was the same for every point $(x,y)$ within the forest. Therefore, one footprint was calculated for the forest and overlaid over the site map and centered over a control ring. When arranged in this manner, the flux values from the footprint grid points that overlaid the four enriching rings on the site map were summed. This represented the total proportion of the upwelling, enriched CO$_2$ that reached that control ring and was considered contamination. This process was duplicated for each control ring. New footprints were calculated for shorter and taller canopy heights and the same overlay procedure was repeated to estimate future contamination levels as the forest grows or is replanted.

2.2. Site

The FACTS-1 site is located within the Duke Forest in Durham, NC (latitude 35°59′N; longitude 78°5′W; elevation 178 m). The stand is a primarily uniform, regenerating loblolly pine ($Pinus taeda$, L.) plantation started in 1982. There are occasional sweetgum ($Liquidambar styraciflua$, L.) and yellow poplar ($Liriodendron tulipifera$, L.) trees mixed in the overstory. Average dominant and co-dominant tree height in 1994 reached to 10.5 m. As previously mentioned, seven circular, 30-m diameter rings are currently in use at the FACTS-1 site. Four of these rings are equipped to maintain the ring at a concentration of 200 μmol CO$_2$ per mole of air above the ambient CO$_2$ concentration (Hendrey et al., 1994). Fig. 1 presents a site map showing the locations of the seven rings within the forest.

Measurements were taken within the prototype ring in October 1994 to determine the micrometeorological effects of the mechanical CO$_2$ dispersing system (He et al., 1996). One hundred and twelve hours of wind and temperature measurements were taken at heights of 1.5, 9.0 and 11.6 m using ATI (Applied Technologies, Boulder, CO; Model SWS-211/3) three-axis sonic anemometers. Statistics generated from these data were used to calibrate the climate data to the site in this study.

2.3. Footprint model

A model primarily based on the work of Horst and Weil (Horst and Weil, 1992, 1994) (hereinafter, referred to as HW92 and HW94, respectively) was developed to calculate the footprint. The contributing flux footprint $f(x,y,z_m)$ (m$^{-2}$), was defined by HW92 as the product of the cross-wind integrated footprint, $f^c(x,z_m)$ (m$^{-1}$), and the cross-wind concentration function, $D_y(x,y)$ (m$^{-1}$).
Fig. 1. Site map of FACTS-1 site within the Duke Forest with 2.5 m contour intervals. The prototype ring is marked FFP and the other six rings are marked R1–R6. Rings 1, 5 and 6 are the control rings, noted with a ‘C’, while the other four are CO2 enriched, ‘E’. Roads within the site leading to each ring are also shown.

\[ f(x, y, z_m) = \frac{\Phi(z_m)}{z_m} \left( \frac{k^2}{T \ln \left( \frac{p^2}{z_0} \right)} - Y \right) \]

(2)

where \( \Phi \) is the normalized cross-wind integrated footprint, \( k \) the von Karmen constant (0.4), \( \phi \) and \( \psi \) the stability functions, \( p \) a constant estimated at 1.55 and \( z \) the mean dispersing plume height. The values for \( d \) and \( z_0 \) were estimated in relation to \( z_h = 10.5 \text{ m} \), where \( d = 0.7z_h \) and \( z_0 = 0.1z_h \). This resulted in a receptor height of \( z_m = 4.2 \text{ m} \). The normalized cross-wind integrated footprint, \( \Phi \), was calculated from HW94 as:

\[ \Phi \equiv \frac{(z_m - d) f^y(x, z_m)}{d \frac{d \bar{z}}{dx}} \]

\[ \approx \left( \frac{z_m - d}{z} \right)^2 \frac{\bar{u}(z_m)}{\bar{U}(z)} A \exp \left[ -\left( \frac{z_m}{b} \right)^\gamma \right] \]

(3)

where \( A \) and \( b \) are gamma functions of \( r \), the shape parameter variable and were presented in HW92. Analytical expressions for \( r \) were described in Gryning et al. (1983). The remaining equations used to solve \( \Phi \) were presented in the HW94 Appendix, but with parameter value modifications of \( \beta = 4.7 \) and \( \gamma = 15 \) following Stull (1988).

The cross-wind concentration function, \( D_y(x, y) \), was assumed to be Gaussian and was calculated from (Gryning et al., 1987):

\[ D_y(x, y) = \frac{\exp \left( -\frac{y^2}{2\sigma_y^2} \right)}{\sqrt{2\pi}\sigma_y} \]

(4)

where \( \sigma_y \) was the standard deviation of the plume in \( y \) estimated from:

\[ \sigma_y = \left( \frac{1.3/L + 0.1}{\sqrt{1 + 0.0001L}} \right) x \]

(5)

where \( L \) is the Obukov length calculated from the climatology data.

2.4. Climatology

Climate data recorded at the Raleigh-Durham airport (RDU), 19.3 km (12 miles) from the site, were obtained from the Southeast Regional Climate Center in Columbia, SC. These data consisted of hourly recordings of wind speed, wind direction, percentage cloud cover, percentage cloud cover opaque, relative humidity and ambient air temperature for 25 years (1965, 1972–1995). There were fewer than 100 h of missing data throughout the 25 years. Calm wind periods were assigned the wind direction of the previous hour and a wind speed of 0.514 m s\(^{-1} \) (1 knot).

The RDU wind speeds and directions were recorded from sensors mounted at 6.1 m (20 ft) at the airport...
and were compared with 112 simultaneous hours of data recorded at the top of the prototype ring in October 1994 (He et al., 1996). The Wilcoxon Signed-Ranked (WSR) test was used to determine significance. The wind directions were not significantly different \( (|p| \leq |S|) = 0.143 \) meaning that the probability of the test statistic, \( S \), being greater than or equal to the resulting value, is 0.143 and, therefore, >0.05, so that the comparing directions are not significantly different. The RDU wind speeds were consistently higher than the wind speeds measured over the prototype ring due to the difference in effective measurement height, \( z_m = 6.1 \) m at RDU vs. \( z_m = 4.25 \) m at the site. A WSR test showed that these were statistically different at the 0.05 level and the RDU wind speeds were scaled by the regression coefficient 0.374 to account for the difference. A WSR test comparing the scaled RDU wind speeds to those measured at the site showed that these numbers were statistically the same \( (|P| \leq |S|) = 0.897 \). Fig. 2(a) presents a composite 25-year wind rose based on the scaled climatology data.

![Wind rose](image)

**Fig. 2.** (a) Wind rose depicting speeds and direction for 25 years of RDU recorded data. (b) Stability rose calculated from the 25-year RDU climate data. Directions for both figures were broken down from the 36 reported to 16 using a random number generator within \( \pm 5^\circ \) for each reported hour.
Each hour of climatology data was categorized using the Pasquill stability classification system (Pasquill, 1961) and wind direction. The classes ranged from very unstable, Class A, through neutral, Class D, to very stable, Class F. The data within each direction and stability class were averaged to estimate values for the Monin–Obukov length, $L$, and friction velocity, $u_s$, that were required for the footprint model. The hours that corresponded to neutral stability, Pasquill Class D, were broken down into day and night periods to more accurately estimate the values of $L$ and $u_s$. Fig. 2(b) presents a composite 25-year stability rose based on the climatology data.

The parameters $L$ and $u_s$ were determined based on the stability of the atmosphere. For a stable air flow, $L$ was calculated from (van Ulden and Holtslag, 1985):

$$ L = \frac{T(u_s)^2}{g(\theta_s)k} \quad (6) $$

where $T$ is the absolute temperature and $\theta_s$ a temperature scale found using the following empirical equation (Venkatram, 1988):

$$ \theta_s = 0.09 (1 - 0.5C^2) \quad (7) $$

where $C$ is the fractional opaque cloud cover. The friction velocity, $u_s$, was determined from (Venkatram, 1980):

$$ u_s = C_{DN}U_{zm}\left\{\frac{1}{2} + \frac{1}{2}\left[1 - \left(\frac{2U_0}{C_{DN}U_{zm}}\right)^{2}\right]\right\} \quad (8) $$

where $C_{DN}$ is a drag coefficient calculated from (Venkatram, 1980):

$$ C_{DN} = \frac{k}{\ln (z_m/z_0)} \quad (9) $$

The wind speed at the point of release, $U_{zm}$, was taken from the climate data and the surface wind speed, $U_0$, was calculated from:

$$ U_0 = \sqrt{\frac{4.7z_m}{\frac{U^2}{u_s^2}}} \quad (10) $$

For unstable flow, or all day periods, estimations of $u_s$ and $\theta_s$ were found using Monin–Obukhov surface layer theory with explanations and supporting equations for Equations (11)–(16) found in van Ulden and Holtslag (1985). Friction velocity, $u_s$, was found from:

$$ u_s = \frac{kU_{zm}}{\ln(z_m/z_0) - \psi(z_m/L) + \psi(z_0/L)} \quad (11) $$

and the temperature scale, $\theta_s$, from:

$$ \theta_s = \frac{-(1 - C)S + 1}{(S + 1)(1 + C_H)\rho C_p u_s} + \alpha \theta_d \quad (12) $$

where $S$ is the slope of the enthalpy curve estimated from:

$$ S = \exp\{0.055(T - 729)\}. \quad (13) $$

The isothermal net radiation, $Q_i^*$, is estimated from:

$$ Q_i^* = K^* - 91 + 60C \quad (14) $$

where $K^*$ is the net shortwave radiation, calculated using a radiation model (Bras, 1990). The model was driven by site-specific climatology data. The empirical heating coefficient of air, $C_H$, can be approximated from:

$$ C_H = 0.38 \left\{\frac{(1 - \alpha)S + 1}{S + 1}\right\}. \quad (15) $$

The heat capacity of air was estimated at: $C_p = 1005$ m$^2$ s$^{-2}$ K$^{-1}$. The empirical temperature scale term, $\theta_d$, was approximated by $\theta_d \approx 0.033$ K and the empirical heating coefficient of the ground, $C_G$, was found from:

$$ C_G = \frac{C_H A_G}{4\sigma T_m^4} \quad (16) $$

where $\sigma = 5.67 \times 10^{-8}$ W m$^{-2}$ K$^{-4}$ is the Stefan–Boltzmann constant and $T_m$ the air temperature (K).

The remaining parameters, required to solve for $u_s$ and $\theta_s$, are $A_G$, an empirical coefficient for the soil heat transfer, and $\alpha$, an empirical moisture parameter. The values for these were determined by comparing the model predictions of $u_s$ and $L$ to measurements taken at the site and finding the best fitting values. The resulting values, $A_G = 5.0$ and $\alpha = 0.63$, were similar to those reported by van Ulden and Holtslag (1983), but remained statistically different at the $p = 0.05$ level using the WSR test ($p > |S| = 0.0222$ and $p > |S| = 0.0243$ for $u_s$ and $L$ respectively).
2.5. Flux estimation

A square (70.56 km$^2$) flux footprint, $f(x,y,z_m)$, was calculated for the forest and was centered over each of the control rings. Fetch, which ultimately determines the footprint domain, has been a topic of debate over the years and is quite variable with stability. HW94 argue for “considerably greater than 100 times the measurement height” during very stable periods. The fetch in this study was set at 1000 times the receptor height, $z_m$, making the square gridded domain 70.56 km$^2$ to account for this.

Once the method for determining the domain size was set, footprints were generated for five other tree heights representing different ages of the forest. These tree heights were: $z_h = 2.0, 5.0, 9.0, 13.0$ and $15.0$ m and resulted in receptor heights of $z_m = 0.8, 2.0, 3.6, 5.2$ and $6.0$ m, respectively. The square domain sizes associated with these tree heights were: 2.56, 16.00, 51.84, 108.16 and 144.00 km$^2$. The final footprints were expressed in terms of average yearly flux (m$^{-2}$) and were based on 25 years of hourly climate data. Day and night contributions were examined and a smaller square domain size, 4 ha, was also generated for each tree height. The complete footprints, centered over the control rings, were placed over the site map to determine the quantity of upward flux at the receptor originating from the CO$_2$ enriched areas.

3. Results and discussion

3.1. Footprint

Fig. 3 presents two views of the 1994 tree height ($z_h = 10.5$ m) footprint of average yearly scalar flux (m$^{-2}$) that reaches a location at the top of the trees. Fig. 3(a) presents the footprint flux values as a percentage of the total flux on a 10-m interval mesh within a 1-km$^2$ domain. Potential CO$_2$ flux contribution from each grid can be obtained by multiplying grid-point percentage values times the average yearly flux density for the stand. This figure is valid at any point over the FACTS-1 site and can be centered over any of the control rings to determine contributions from CO$_2$-enriched areas. Hourly changes in stability and wind direction account for the variations of flux over the footprint.

The center of the footprint contains concentrations of flux that are 5–6 orders of magnitude greater than points 500 m away. A comparison of the footprint with the wind and stability roses highlights the effect of stable conditions on far-field flux particularly for the SSW and ESE directions. Fig. 3(b) presents the data as a contour map that can be superimposed over any location at the site. The contours represent lines of equal contribution and the associated percentage values are the cumulative contribution from the center out to that line.

Fig. 4 presents a graph of total average annual flux to a point at the canopy top at the FACTS-1 site. The flux was split into night and day contributions for the six forest heights and increased with tree height. This was due to the greater distance of the receptor height, $z_m$, for the taller trees. The night component increased with forest height and controlled the shape of the total flux while the day component remained fairly constant.

Flux calculations for smaller, 4-ha square domains were also calculated for each forest height to separate near-field potential flux contributions to the total. The percentages of 4-ha flux to the total were 86, 71, 55, 52, 47 and 42% for the 2-, 5-, 9-, 10.5-, 13- and 15-m forest heights, respectively. Breaking the 4-ha flux down by day and night contribution showed fairly constant day values for each forest height but decreasing night values. This result indicated the far-field contributions were of increasingly greater importance during stable conditions as the forest matures.

3.2. Potential control ring contamination

The potential control ring contamination was determined by superimposing the scalar flux footprint over the center of each control ring and summing the average yearly scalar flux (m$^{-2}$) contributions emanating from the four CO$_2$-enriched rings. Fig. 5 presents the proportion of total flux at the top of the control rings from the enriched rings with breakouts by day and night. For the 1995 tree height, $z_h = 10.5$ m, ring 5 received the highest levels of contamination where 0.9% of the total yearly average flux originated from the enriched rings. This percentage was not considered to be very high and was confirmed using the cumulative footprint shown in Fig. 3(b). Ring 6 received
Fig. 3. (a) Percent contribution of total flux to the receptor point from each footprint grid. The figure domain is 1 km$^2$.
(b) Contour map of the average yearly flux footprint with contour lines indicating equal contribution to the center point. The percentage values listed on the figure are the cumulative flux contribution to the center point from the area inside the contour.
the next highest potential contamination level at 0.8% and Ring 1 the least at just over 0.5%. The differences in the contamination levels stem from the proximity and direction of the rings to each other as expected after comparing the site map with the stability roses. The levels of contamination changed with tree height, generally increasing to $z_h = 9.0$ and then slowly decreasing with taller trees. The levels never exceeded 1% for any ring at any tree height due primarily to the distance they were set from one another.

Fig. 4. Footprint estimate of total average yearly flux ($m^{-2}$) for multiple tree heights. Columns are split into the day and night contributions.

Fig. 5. Potential average yearly flux to each control ring (rings 1, 5 and 6 marked on corresponding bars) originating from the CO$_2$-enriched areas as a percentage of total flux into the control rings for the six forest height considerations.
Levels of potential contamination were very small, but the night component was 3–7 times greater than the day. Therefore, enrichment during the night is much more likely to result in control ring contamination while the day contamination potential is virtually negligible by comparison. Remembering that this analysis considers only the upwelling CO$_2$ component and that actual net CO$_2$ flux is negative (toward the surface) during the day, it is extremely unlikely that any CO$_2$ from the enriched areas would reach the control rings during the day.

This study considered the time averaged CO$_2$ contamination, not episodic variability. Micrometeorological processes act to pass large parcels of air in and out of the rings translating to periods of virtually no contamination to other periods of high contamination. The mean daily Duke Forest CO$_2$ flux as measured by eddy covariance is $-0.27$ mg m$^{-2}$ h$^{-1}$ (Katul et al., 1997). The peak day CO$_2$ flux is $-1.6$ mg m$^{-2}$ h$^{-1}$ and peak night time flux is $0.7$ mg m$^{-2}$ h$^{-1}$ (Katul, 1998, personal communication). Episodic high contamination periods may have ecological effects but cannot be described using a temporally averaged footprint climatology.

### 4. Conclusions

Footprint climatology was used to assess the potential impact of control ring contamination at the Duke Forest FACTS-1 experimental site. The results presented in this paper are based on the physical forest and climate data found in the Duke Forest. However, the model described can be applied to any site in any climate provided data is available. Calibration of climate data by local, short term measurements is a simple technique that makes footprint climatology analysis applicable to many situations.

The levels of potential CO$_2$ contamination from the four continuously enriched rings into the three control rings differ due to the spatial arrangement of the rings at the FACTS-1 site. Footprint estimates showed a small but noticeable potential contamination effect on the control rings from the CO$_2$-enriched rings at the current forest height. A breakdown of the potential contamination into day and night components revealed that night contamination levels were greater than three times the day levels for all three control rings. For taller tree heights, the associated footprints showed a net decrease of potential contamination into the control rings due to decreased night levels. This reduced night contamination effect is caused by the increasing total contributing area (i.e. fetch) and associated flux as the receptor height, $z_m$, gets higher.

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