

Sub-canopy deposition of ozone in a stand of cutleaf coneflower

Peter L. Finkelstein^{a,*}, Alan W. Davison^b, Howard S. Neufeld^c,
Tilden P. Meyers^d, Arthur H. Chappelka^e

^aAtmospheric Modeling Division, NOAA; on assignment to the U.S. EPA, Research Triangle Park, NC 27711, USA

^bSchool of Biology, University of Newcastle, Newcastle upon Tyne NE1 7RU, England, UK

^cDepartment of Biology, Appalachian State University, Boone, NC 28608, USA

^dAtmospheric Turbulence and Diffusion Division, NOAA, P.O. Box 2456, Oak Ridge, TN 37830, USA

^eSchool of Forestry and Wildlife Sciences, 108 M. White-Smith Hall, Auburn University, Auburn, AL 36849, USA

Received 27 August 2003; accepted 6 February 2004

“Capsule”: *Observed ozone profiles within a dense herbaceous perennial stand are reproduced using a higher-order closure model of turbulence and deposition.*

Abstract

Although there has been a great deal of research on ozone, interest in exposure of native, herbaceous species is relatively recent and it is still not clear what role the pollutant has in their ecological fitness. The ozone exposure of a plant is usually expressed in terms of the concentration above the canopy or as a time-weighted index. However, to understand the physiological effects of ozone it is necessary to quantify the ozone flux to individual leaves as they develop, which requires knowing the deposition velocity and concentration of the pollutant as a function of height throughout the plant canopy. We used a high-order closure model of sub-canopy turbulence to estimate ozone profiles in stands of cutleaf coneflower (*Rudbeckia laciniata* L.) located in the Great Smoky Mountains National Park, USA. The model was run for periods coinciding with a short field study, during which we measured vertical concentration profiles of ozone along with measurements of atmospheric turbulence and other meteorological and plant variables. Predictions of ozone profiles by the model are compared with observations throughout the canopy.

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Keywords: Ozone; Deposition; Flux; Sub-canopy; *Rudbeckia laciniata*

1. Introduction

Ozone concentrations in many parts of the developed world are sufficiently high to cause visible injury to sensitive plant species. For example, in Great Smoky Mountains National Park (GSMP) about 25–30 species develop typical symptoms during July and August in most summers (Neufeld et al., 1992; Chappelka et al., 2003). Some of the more sensitive species include crown-beard (*Verbesina occidentalis* (L.) Walter), tall milkweed (*Asclepias exaltata* (L.)) and cutleaf coneflower (*Rudbeckia laciniata* (L.)). Although there has been a great

deal of research on ozone, interest in the effects on native, herbaceous species is relatively recent and it is still not clear what effects the pollutant has on their ecological fitness (Davison and Barnes, 1998). This paper is part of a comprehensive study that has the goal of determining the biochemical, physiological, ecological and genetic effects of ozone using a common native species, cutleaf coneflower, as a model.

Cutleaf coneflower is a forest edge plant that grows along the boundary between field and forest. It is abundant in the Purchase Knob area, Clingman's Dome, and other locations within the GSMP. Stands range in size from a meter to more than 20 m across, and may run along a forest edge for hundreds of meters. The plants are typically 1.5–2 m high, with the most dense foliage about

* Corresponding author.

E-mail address: finkelstein.peter@epa.gov (P.L. Finkelstein).

20–80 cm from the ground. Flowering is typically in July and August. In this species, exposure symptoms start as patches of dull-red, mottled areas (stipples) between the veins of the upper surfaces of the lower leaves. The mottle may develop into tan or brown necrotic patches and the affected leaves senesce prematurely. As the season progresses, the symptoms often spread up the plant to the youngest leaves and the floral bracts. In previous papers we have reported on the variation in symptom expression, genetic diversity within populations, stomatal conductance and gradients in light and ozone within canopies (Chappelka et al., 2003; Davison et al., 2003). The data show that there is marked variation in the degree of injury exhibited by individual plants within and between plant populations that are relatively close to each other (Chappelka et al., 1997, 2003). In one population the degree of injury differed greatly within a single genet, pointing to a micro-environmental influence on symptom expression which we tentatively suggested may be due to variation in light (Davison et al., 2003). It was considered unlikely to be caused by differences in stomatal conductance or ozone concentrations.

The degree of ozone exposure of a plant is usually expressed in terms of the concentration at a reference point above the canopy or as a time-weighted index such as the SUM06 or AOT40. Although these are easily measured, they do not give an indication of ozone concentrations at the leaf surfaces or flux through the stomata. As plants develop from spring onwards, increasing in height and leaf area index, the degree of ozone penetration into the canopy changes so that successive leaves are exposed to different combinations of ozone, light, temperature and humidity. The changes in environment alter stomatal conductance and therefore ozone flux. In addition, the stomata respond to environmental factors such as vapor pressure deficit and water stress; so conductance and flux alter over time scales of hours or days independent of the ambient ozone above the canopy. Therefore, to understand the patterns of symptom development that we have observed and to be able to relate the physiological effects to ambient ozone, it is necessary to determine the relationships between ozone above the canopy and at each leaf surface. Eventually the goal is to be able to estimate the flux to each leaf during its life and relate it to the physiological effects.

Since the technology to measure flux to an individual leaf in the field has not been developed, we have to rely on models of sub-canopy deposition for an estimate. In this study we compare predictions of ozone profiles made with a sub-canopy deposition model to measured profiles of ozone within the canopy. Because the ozone profile is a direct result of turbulent mixing within the canopy and the deposition of ozone to the adjacent leaves, successful modeling of the ozone profile implies successful modeling of turbulent transport, deposition, and flux as functions of height within the canopy.

Wind speed and turbulence profiles are rather complex within a plant canopy and do not follow the simple log law of wind profiles that are found in a normal meteorological boundary layer. Therefore gradient transfer theory as is usually used is not appropriate (Shaw, 1977, 1985; Denmead and Bradley, 1985). Instead we must rely on higher-order closure models (Stull, 1988) to represent the mixing processes that go on in a canopy. We have chosen for this study a model developed by Meyers and Paw U (Meyers and Paw U, 1986, 1987; Paw U and Meyers, 1989) which utilizes higher-order closure theory to represent the wind and turbulence profiles. The Meyers and Paw U (M–P) model also includes a radiation model to estimate the amount of light reaching each leaf, and a dry deposition model to estimate the flux of pollutant at each level within the canopy.

2. Materials and methods

2.1. Location

The Great Smoky Mountains National Park is an International Biosphere Reserve and World Heritage Site. The Park straddles the North Carolina–Tennessee border, in the southeastern United States. The study took place within the Park at the Purchase Knob—Appalachian Highlands Science Learning Center (35.588°N, 83.074°W), which is in the eastern end of the Park. The Purchase site consists of approximately 200 ha of high-elevation (1400–1500 m) forests and fields. Measurements were taken at two locations: in a stand of coneflower on the outside edge of a forest–field boundary, about 20 m from the well-defined edge of the forest, and at a second site about 30 m inside the tree canopy, and about 70 m from the outside site. In the vicinity of the stands the terrain was quite level, near the top of a ridge, but the terrain sloped away steeply to the northeast within 100 m.

At both the outside and inside study sites the coneflower stands were very homogenous in composition and were quite dense. At the outside site, the population had a height of 1.2 ± 0.2 m. The LAI of the stand was approximately 3. Inside the forest, the light was approximately 2%–10% of full sunlight, apart from sunflecks. Consequently the coneflowers were a bit taller (1.4 ± 0.2 m) but not as dense (LAI ≈ 2). The forest canopy was predominately yellow buckeye (*Aesculus flava* Soland), with some maple and oak species (*Acer* and *Quercus* spp., respectively). Overstory trees ranged in height from 9 to 30 m, with an average crown height of 11 ± 3 m (live crown ratio of 60%). The forest stand averaged about 500 total stems/ha, with an average diameter in the range 25–35 cm.

2.2. Ozone instrumentation

Ozone was measured using four 2B Technologies ozone monitors. These monitors work on the principal of UV absorption at 254 nm. The monitors were all calibrated at the factory before the field program, and checked in our lab against a primary reference standard. Every two days in the field the instruments were checked for zero by putting a charcoal filter in the line, and adjusting the zero offset if needed. These adjustments were usually very small. The instruments were also intercompared every two days by placing the inlets together, using the inlet line and filters used in the field. Because we are interested in differences rather than absolute accuracy, the most stable instrument was selected as the reference instrument, and a linear regression was developed to set each of the other instruments to be as equivalent as possible to the reference instrument. Outputs reported here have been corrected by this method.

In the field, the inlet lines (Teflon) were tied to a pole placed in a dense part of the stand. The inlets were set to four heights as shown in Table 1. Because of the occasional appearance of feral hogs in the local forest, and noting their deleterious effect on the operation of sensitive instrument, the ozone and meteorological instruments were removed from the field each evening, and reassembled in the morning.

2.3. Meteorological instruments

Wind speed and turbulence measurements were made with an R. M. Young model 81000 sonic anemometer. The sonic anemometer was mounted on a tripod tower at about 2.3 m above the ground, and within 8–12 m of the ozone profile system. After the experiment a 2-axis rotation algorithm (Wilczak et al., 2001) was applied to half-hour raw data files, then the first, second, and third moments of the wind vector were computed.

Standard global, net, and photosynthetically active radiation (PAR) measurements were made, along with temperature and relative humidity (in a non-aspirated shield). These instruments were also mounted on the tripod tower. The heights of the sonic and other instruments are given in Table 1.

Table 1
Heights (m) of ozone and meteorological measurements at the site outside the forest edge, and inside the forest canopy

Measurement	Outside site (m)	Inside site (m)
O ₃ -1	2.35	2.32
O ₃ -2	1	0.78
O ₃ -3	0.57	0.46
O ₃ -4	0.2	0.18
Anemometer	2.3	2.5
Other met.	1.25	1.25
Canopy height	1.2 ± 0.2	1.4 ± 0.2

2.4. LAI and leaf conductance

LAI profiles were made by making measurements at several heights within the coneflower canopy, at both the inside and outside sites. Repeated profiles were made at each site, and several locations were used within the area of the ozone profile. Measurements were made with a Li-Cor LAI-2000 Plant Canopy Analyzer (Li-Cor Inc., Lincoln, NE, USA).

At the start of the study, five individual plants at each site were numbered and the uppermost and lowermost (non-senescent) leaf on each plant marked. The stomatal conductance of the adaxial surface of each upper and lower leaf was measured at approximately hourly intervals using a Delta T Mark IV porometer. The instrument was calibrated at 1–2 h intervals, and cross-checked against a Li-Cor 6200 instrument that was being used at the same time to measure net assimilation rates.

2.5. Model description

To analyze and predict deposition and ozone concentrations within the coneflower canopy we use a layered, plant-canopy model originally developed for tree canopies. The M–P model has three main components. The first is a model of atmospheric turbulence within and above the plant canopy which mixes the pollutants down into the canopy. The second is a radiation model which estimates light levels throughout the canopy and is used both for heat input into the canopy, and for control of the stomata. The third is a deposition model, which estimates the transport of pollutant (the flux) to the leaf stomata, plant surfaces, and soil.

The turbulence component of the M–P model uses a higher-order closure method to predict the first through fourth moments of the wind velocity, temperature, and water vapor. The fourth moment terms are solved using a quasi-Gaussian distribution assumption which relates them to second moments. The results of the turbulence model are linked to an energy budget and leaf physiology model. The model uses 61 layers, the first 20 in the plant canopy, and the others in the air above. Within each plant canopy layer the energy budget is solved exactly (Paw U and Meyers, 1989). Deposition involving leaf stomatal resistance is calculated from considerations of the latent heat budget, and assumed to be inversely proportional to the visible radiation flux density. The soil boundary layer is handled by assuming a soil resistance, which separates a moist soil interior from the atmosphere. Radiation within the canopy is modeled with a modified version of the Norman (1979) (see also Meyers et al., 1998) radiation model, assuming a spherical leaf angle distribution. The leaf boundary layer resistance, r_b , follows the formulation of Meyers

et al. (1998) and Norman (1979) in which r_b is inversely proportional to the square root of the mean wind speed.

Within the model, conservation equations for heat, moisture, and momentum, and their corresponding fluxes are coupled with the radiation in the canopy, and the biological factors (such as stomatal resistance) to simulate the detailed micro-environment of the plant canopy. The diffusivity of ozone is used to adjust the stomatal resistance for water vapor to the appropriate values for those gases. Then the flux at each level, and the resulting concentration at each level can be calculated.

Inputs to the M–P model are the canopy height, total LAI, leaf area density profile, minimum stomatal resistance, drag coefficient (C_d), location and time (to compute the sun angle), global radiation, wind speed, temperature, relative humidity, plant specific light response coefficient (Meyers and Paw U, 1987, Eq. (2)), concentration of ozone above the canopy, and the heights of the various measurements. Outputs include profiles of wind speed, temperature, latent and sensible heat, radiation at various wavelengths, pollutant concentration and flux, and various higher moments of the turbulence field, from the ground to three times the height of the canopy.

3. Results

3.1. Observations

Because of adverse weather and other limitations, observations of ozone profiles and accompanying meteorological variables could only be made on four

days, July 27, 28, 30, and 31, 2002. On the 27th and 28th the measurements were made at the site on the outside edge of the forest. On the 30th and 31st the instruments were inside the forest canopy. On all the days the sky was partly cloudy, with showers in the vicinity, but missing our mountain-top site. The winds were light and predominantly from north to northeast.

3.1.1. Ozone

Ambient ozone 30 min concentrations were low (20–40 ppb) at the Purchase site on the 27th, 28th, and 30th of July. They increased to about 65 ppb on the 31st. The ozone concentrations at four levels (three on the 31st, due to instrument problems) are shown in Fig. 1. The uppermost level is approximately 1 m above the coneflower canopy, and is what we are referring to as ambient. The second level is just within the canopy, but above the dense vegetation. The third level was located in the most dense part of the canopy, and the fourth level was close to the ground. As can be seen from the figure, the concentrations at all levels follow the fluctuations of the ambient concentration. Even when looking at the 1-min averaged data, no time lag is apparent between levels. The second level is very similar to the first, as little uptake has taken place. The third level is significantly less than ambient, and the fourth is reduced still more. The amount of reduction between ambient and the lowest level is quite consistent, with 49% reduction on the 27th, 42% on the 28th, 45% on the 30th, and 38% on the 31st.

3.1.2. Meteorology

Wind speeds were between 0.1 and 1 m/s on the 27th, 28th and 30th, and between 1 and 2 m/s on the 31st. As

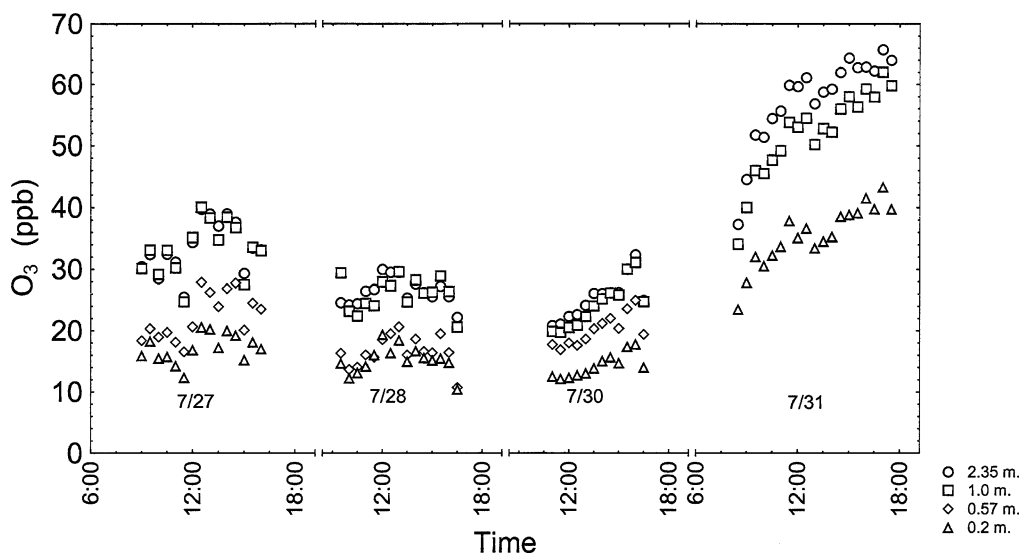


Fig. 1. Time series of ozone (ppb) observed above and within a stand of cutleaf coneflower. The highest level (2.35 m) is above the canopy, the others are within it. Profiles on the 27th and 28th are taken at the site on the outside edge of the forest. Profiles on the 30th and 31st are taken at the site within the forest canopy.

will be discussed below, the very light winds limited our ability to evaluate the model because of instabilities in the numerical formulation of the model. However, we can see that since the lowest ozone levels followed the ambient concentration quite well (Fig. 1), there was enough mixing to move air into the lowest levels of the coneflower canopy.

Photosynthetically active radiation (PAR) measurements at the outside site on the 27th and 28th range from about $400 \mu\text{mol m}^{-2} \text{s}^{-1}$ in the morning when the station was started to highs in the range of 1200, and lows of 200 when the station was shut down for the evening. At the inside site, the light was much reduced by the forest canopy. Morning values were in the range $20\text{--}50 \mu\text{mol m}^{-2} \text{s}^{-1}$, with daytime highs of $100\text{--}120$, and evening lows of 20 or less. Variability was large, caused mainly by clouds and sunflecks.

3.1.3. Stomatal resistance

Stomatal resistance measurements were made at 1–2 h intervals throughout the sampling period each day. Measurements from the upper leaf are shown in Fig. 2. The standard error of the observations averaged approximately 7% of the measurement values. Note that both the inside and outside site leaves have minimal stomatal resistance from morning through mid-afternoon, with very little change in value in spite of changes in light levels. Although light levels inside the forest canopy are much less, the stomatal resistance of the inside leaves is close to or at most 50 s/m more than the minimum resistance of the leaves at the outside stand. Only late in the afternoon when the PAR values drop to $10\text{--}40 \mu\text{mol m}^{-2} \text{s}^{-1}$ do the resistances of the coneflower leaves increase appreciably. The resistance of the leaves outside the forest also increases late in the afternoon. Interestingly their resistances at PAR values around

$200 \mu\text{mol m}^{-2} \text{s}^{-1}$ are equal to, or slightly greater than those of the inside site leaves with PAR values of $100 \mu\text{mol m}^{-2} \text{s}^{-1}$ or less. These diurnal patterns of resistance were similar to those recorded in previous years (Davison et al., 2003).

3.1.4. Turbulence

Turbulence levels, as measured by σ_w , the standard deviation of the vertical wind speed, would be expected to be lower under the tree canopy than at the outside site, and they are. Average σ_w values during the day are $0.23 \pm 0.007 \text{ m/s}$ (standard error) on the 27th, 0.26 ± 0.02 on the 28th, 0.12 ± 0.007 on the 30th, and 0.18 ± 0.006 on the 31st. In spite of these differences the reduction in ozone between the highest and lowest levels, as noted above, is quite consistent across the four days.

3.2. Model application

Half-hour average values of the various meteorological variables measured on site were used in the M–P model. Other input parameters that were used are the drag coefficient, $C_d = 0.21$, and the light response coefficient, $\Phi = 90$. Minimum stomatal resistance (r_{\min}) was taken from the site measurements and simplified to $r_{\min} = 50 \text{ s/m}$ at the outside site, and $r_{\min} = 100 \text{ s/m}$ at the inside site. Several LAI profiles were measured. From them a leaf area density profile was developed which has most of the leaf mass in the lowest parts of the canopy.

We found that various combinations of input variables, usually including very low wind speeds, caused numerical instabilities in the model. Because the wind speeds were very light on the 27th, 28th and 30th, only a few periods could be modeled on those days. Most of the half-hour measurement periods on the 31st were modeled.

Fig. 3 presents typical vertical profiles of ozone and wind speed from the model. Two examples are given, one from 13:00 on the 27th and one from 09:00 on the 31st. The differences are a consequence of the different input variables. The ozone profiles are seen to decrease slightly above the canopy ($z > H$, where H = height of the canopy), with a faster decrease with height within the canopy ($z < H$). The decrease above the canopy is caused by the stomatal uptake and ozone deposition on the external plant surfaces and the soil, and the depleted air being mixed downward by turbulence. The degree of mixing determines the slope of the profile. Below the canopy top, the direct effects of stomatal uptake are seen in addition to atmospheric mixing, and the uptake rate is increased. The uptake rate on the 31st is less, in part because of the diminished light levels within the forest canopy which decreases stomatal conductance. The profiles of wind speed for the same two cases also show

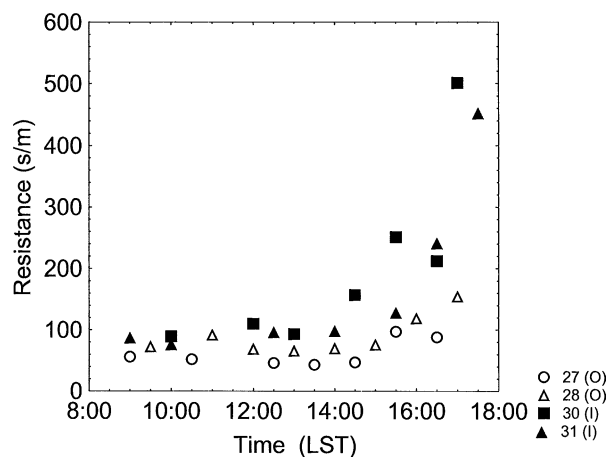


Fig. 2. Stomatal resistance (s/m) of the upper leaves of the cutleaf coneflower measured throughout the day on the four experimental days near the ozone monitoring site. Each value shown is an average of several measurements taken on different leaves in the vicinity.

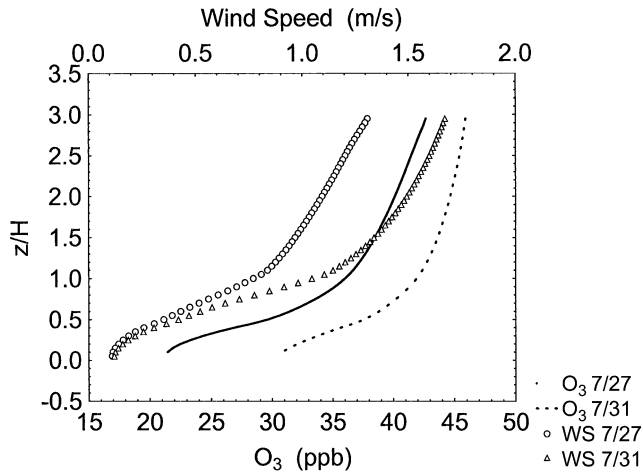


Fig. 3. Vertical profiles of ozone (ppb) and wind speed (m/s) from the M–P model at two times, 13:00 on the 27th and 09:00 on the 31st. These examples are typical of model output.

an inflection point at the top of the canopy, caused by the direct effect of the drag of the plants. In all cases, the wind speed is forced to zero at the ground surface.

Limited comparisons of model predictions of ozone concentration within the canopy are shown in Fig. 4 A and B. In Fig. 4A the observed ozone at 2.3, 1.0, 0.6, and 0.2 m are shown for five half-hour averages on the 27th. The model estimate at $z = 1.0$ m, just below the top of the canopy, shows a larger decrease in ozone than is observed. The observed ozone shows almost no decrease over that above the canopy, which may indicate that mixing into the sparse top of the canopy is greater than indicated by the model. Model agreement at the lowest two levels is within a few ppb of observed values for all times but 13:30, when the model predicted 4–5 ppb higher ozone levels than were observed. No reason for the larger bias during this time period is obvious. Fig. 4B shows the same information for the 31st, within the forest canopy. The ozone monitor at 0.5 m was unreliable on this day, and is not shown. In this case the model was within 1 ppb at all times at the 0.78 m height. The observed ozone concentration at the lowest level had been depleted by 3–10 ppb more than the model predicted, with the highest bias during the middle of the day. (Note that the model was not run for the last few periods of the day because of very low wind speeds.)

Ozone concentrations in the canopy are determined by the rates of uptake by the plants and by the degree of atmospheric mixing caused by turbulence. We can compare model predictions of the second and third moments of turbulence with measurements made at the height of the sonic anemometer, which was about a meter above the coneflower canopy to evaluate that portion of the model's performance. Model predictions and observed values are shown in Figs. 5 and 6. Turbulent energy components, the second moments

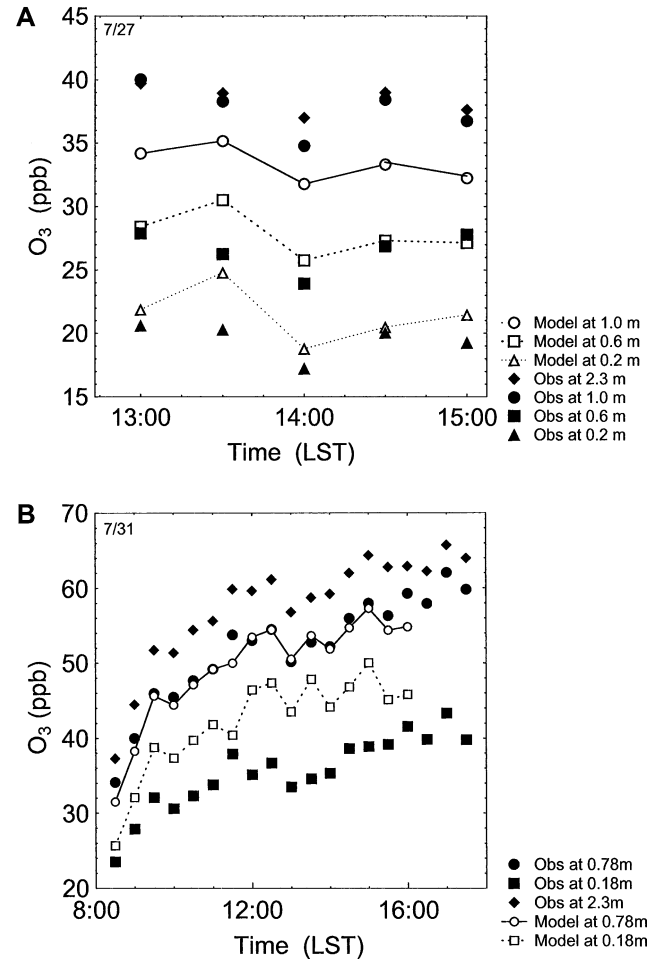


Fig. 4. Comparisons of M–P modeled and observed ozone concentration (ppb) within the cutleaf coneflower canopy at the outside site on the 27th (A) and inside site on the 31st (B).

(u'^2 , v'^2 , and w'^2), are given in Fig. 5A and B. On the 27th the model agrees with the observed vertical turbulent energy, w'^2 . It underpredicts the horizontal components parallel to the mean wind, u'^2 , and perpendicular to it, v'^2 . On the 31st, within the tree canopy, (Fig. 5B) the model overpredicts w'^2 , but continues to underpredict the u'^2 and v'^2 terms. Note that at the outside site the v'^2 observations are significantly less than those of u'^2 , but similar to them at the inside site. Larger u'^2 than v'^2 observations are more typical in the free atmosphere. The fact that they are more nearly equal within the forest canopy suggests that the influence of the forest on mixing has redistributed, and reduced, the turbulent energy.

A note of caution must be given about the accuracy of the measurements. Finkelstein and Sims (2001) have shown that individual measurements of various atmospheric fluxes can have substantial random error (10–30%). In this rough boundary layer, one might expect the errors to be even higher. However, these are random errors, and the fact that the biases are consistent

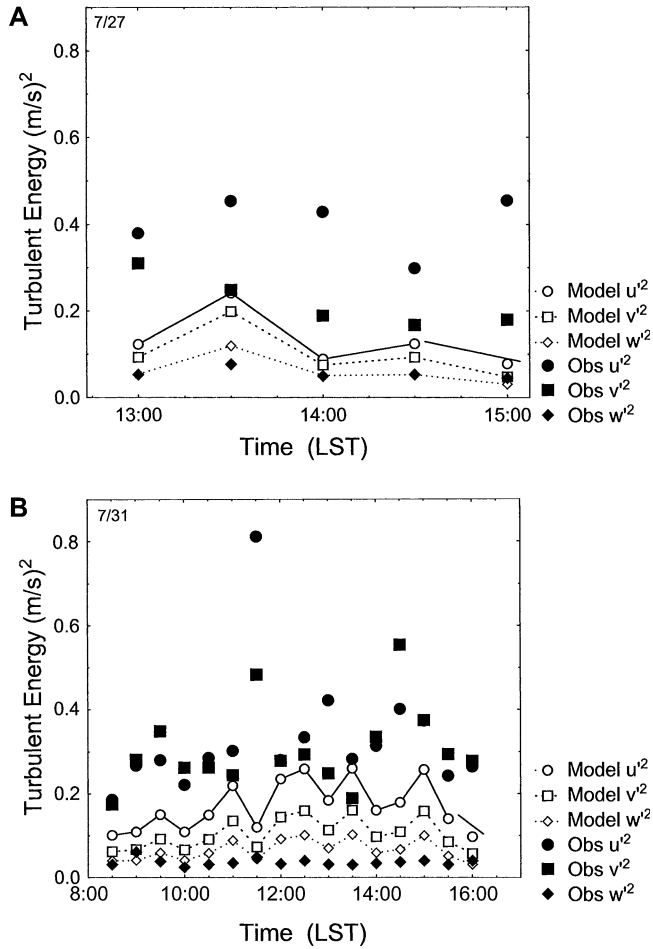


Fig. 5. Comparisons of turbulent energy ((m/s)²) predicted by the M–P model at the outside site on the 27th (A) and the inside site on the 31st (B). Primes denote departure from the mean value, e.g. $u'^2 = (u - \bar{u})^2$.

in sign indicates some confidence in the inference that can be drawn about model performance.

The third moments of vertical turbulence, w'^3 , $w'u'^2$, and $w'v'^2$, are shown in Fig. 6A and B. The model predicts small negative values at the outside site, and small positive values at the inside site. This difference is related to the amount of sunshine (heating) and its effect on the transport of energy in the canopy. The vertical mixing of horizontal energy has, for the most part, the correct sign, and a small bias. The vertical mixing of vertical energy has a bit more scatter in sign, but the bias is again small. At the inside-the-forest site the observations frequently, but not always, have the same sign as the model, but there is quite a bit more scatter. This may be explained by the fact that this turbulence is generated in large part by the wakes of the trees, which is not a factor considered by the model.

Two example profiles of ozone flux from the model, corresponding to the time periods used in Fig. 3, are shown in Fig. 7. Note that the flux above the canopy ($z/H > 1$) is a constant whose value depends upon the

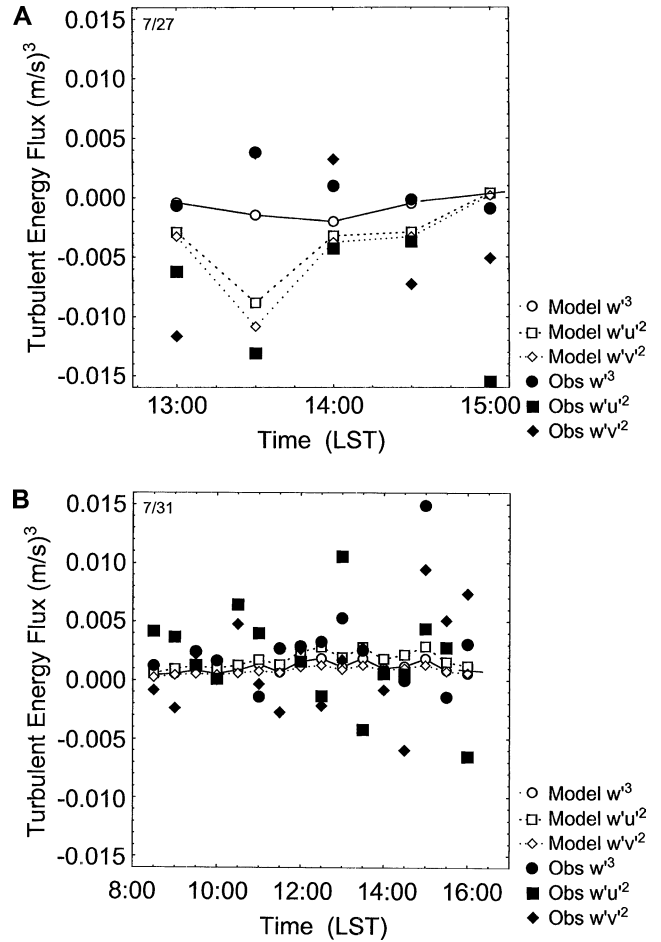


Fig. 6. Comparisons of third moments of the turbulence field ((m/s)³) at the outside site on the 27th (A) and the inside site on the 31st (B). (In A at 13:30, the symbol for $w'v'^2$ is obscured by the symbol for $w'u'^2$.)

overall uptake of the canopy and the atmospheric mixing. The total modeled flux on the afternoon of the 27th was about twice that of the 31st, due to less mixing, less light, and higher stomatal resistance. The rate of decrease in the flux corresponds to the amount of ozone being taken up by the vegetation in each layer, and is assumed to reach zero at the ground.

4. Discussion and conclusions

Measurements of ozone concentration profiles in stands of cutleaf coneflower, both on the outside edge of, and within a forest canopy show a decrease of ozone as one descends into the canopy from above. Ozone concentrations near the ground (20 cm) are roughly one-half of the values measured 1 m above the stand. The decrease is slightly less at the inside site where the LAI is lower.

Measurements of meteorological variables, LAI profiles, and leaf conductance were used in the M–P model, a higher-order closure, sub-canopy diffusion and

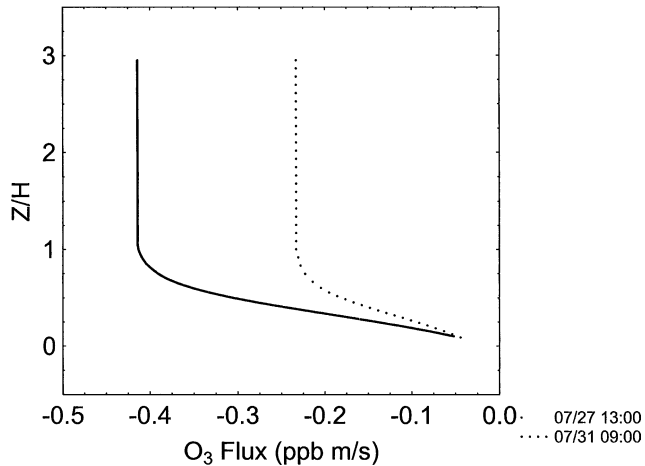


Fig. 7. Examples of the vertical profile of ozone flux (ppb m/s) predicted by the M–P model at 13:00 on the 27th at the outside site, and at 09:00 on the 31st at the inside site.

deposition model to predict ozone concentrations within the canopy. Our assumption is that if the model is able to predict ozone concentration in the canopy, then the deposition velocity and flux, which account for much of the loss of ozone, must also be reasonably accurately predicted. Limited comparisons of measured and predicted ozone concentrations on two days at various levels within the canopy are shown (Fig. 4). On one series of observations in the stand on the outside edge of the forest canopy the model underpredicted by 3–5 ppb at a height just below the top of the stand, and overpredicted by 0–4 ppb in the middle and lower parts of the stand. In the other series of tests, inside the forest canopy, the model's predictions at mid-level were quite accurate, while it overpredicted the ozone concentrations at the lowest level by about 5 ppb.

The overprediction at the lowest levels, which occurred on both days, implies that there is more ozone uptake than what the model predicts. Since there are very few active leaves at this level, the reason is probably not increased stomatal or leaf surface uptake. It may be due to other factors, including lower than expected mixing at the lowest levels, larger than expected conductance to the soil, or titration of the ozone by NO released from the soil. Generally one does not expect release of NO from an undisturbed forest soil, but no measurements have been made in this ecosystem, so the question is still open. Further investigations into all possibilities will be needed to explore these options. The results presented here are limited, but encouraging enough for us to continue further field studies and model refinement.

Comparisons of the second and third moments of turbulence with modeled values above the canopy, which are an independent way to evaluate another part of the model, show, on average, modest bias, but considerable scatter, especially in the third moments.

Consideration of the shape of the profiles of these terms suggests that for better evaluation of this part of the model, measurements of turbulence at locations within the canopy are important, as it is at these locations that the profiles are most variable. Improvements in the predictions of turbulence at the lowest levels may lead to an improved understanding of the modeled ozone overprediction.

Knowing the ozone flux as a function of height within the canopy, which may now be possible from models such as the one demonstrated here would allow one to estimate the ozone exposure of individual leaves in a plant stand, and to compare ozone exposure to damage symptoms in order to better understand the response of plants to injurious pollutant stresses. Having exposures and fluxes at the leaf level will be a significant improvement over attempting to relate plant damage to concentrations measured above the stand, and should lead to better relationships between pollutant levels and plant injury.

Acknowledgements

We would like to thank National Park Service personnel Susan Sachs, Paul Super, and Jim Renfro from the Great Smoky Mountains National Park for their hospitality and assistance with this research; and Donna Schwede of the Atmospheric Modeling Division, NOAA for her help with the M–P model. This research was funded in part by the National Geographic Society, the U.S. Environmental Protection Agency, the National Park Service (PMIS#66941) and the Graduate School at Appalachian State University. This paper has been reviewed and approved for publication by both the Environmental Protection Agency and the National Oceanic and Atmospheric Administration. Mention of commercial products does not constitute an endorsement for use by either agency.

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