Ozone and Carbon Dioxide Fluxes in a Subalpine Spruce-fir Forest Ecosystem[1]

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Introduction

RMFRES RWU 4452 has made several ozone (O_3) and carbon dioxide (CO_2) trace gas flux measurements in the Snowy Range, WY GLEES research area over the past few years. These measurements were made using the micrometeorological eddy correlation technique at two sites: one 6 m above tree canopy height on the Brooklyn tower (ozone only); and the other below canopy height, 1-2 m above a wet alpine meadow surface near the Brooklyn tower. Diel CO_2 vertical flux cycles change dramatically from expected daytime uptake (downward) and nighttime emissions (upward) during the growing season to predominantly upward during winter above the snow surface. Diel O_3 vertical flux cycles above the tree canopy vary from normal deposition during the summer growing season to upward in the presence of snow cover. Diel O_3 vertical flux cycles above the wet meadow are downward (deposition) as expected year round, however wintertime deposition measured above 1-2 m snow depths are significantly smaller than fluxes measured above snow cover reported in the literature.

Ozone and Ozone Fluxes

Above Tree Canopy

Forest ecosystems play a role in the uptake and destruction of tropospheric O_3. This role and the tropospheric O_3 budget in remote forested ecosystems is uncertain [Lefohn, 1992]. The known rate of O_3 deposition is rapid during the growing season and slower during winter months [Wesely, 1983]. Ozone deposition is retarded further by surface snow cover [Wesely et al. 1981, Stocker et al. 1995]. Our data show the unexpected effect of snow cover on O_3 fluxes as measured on the Brook-

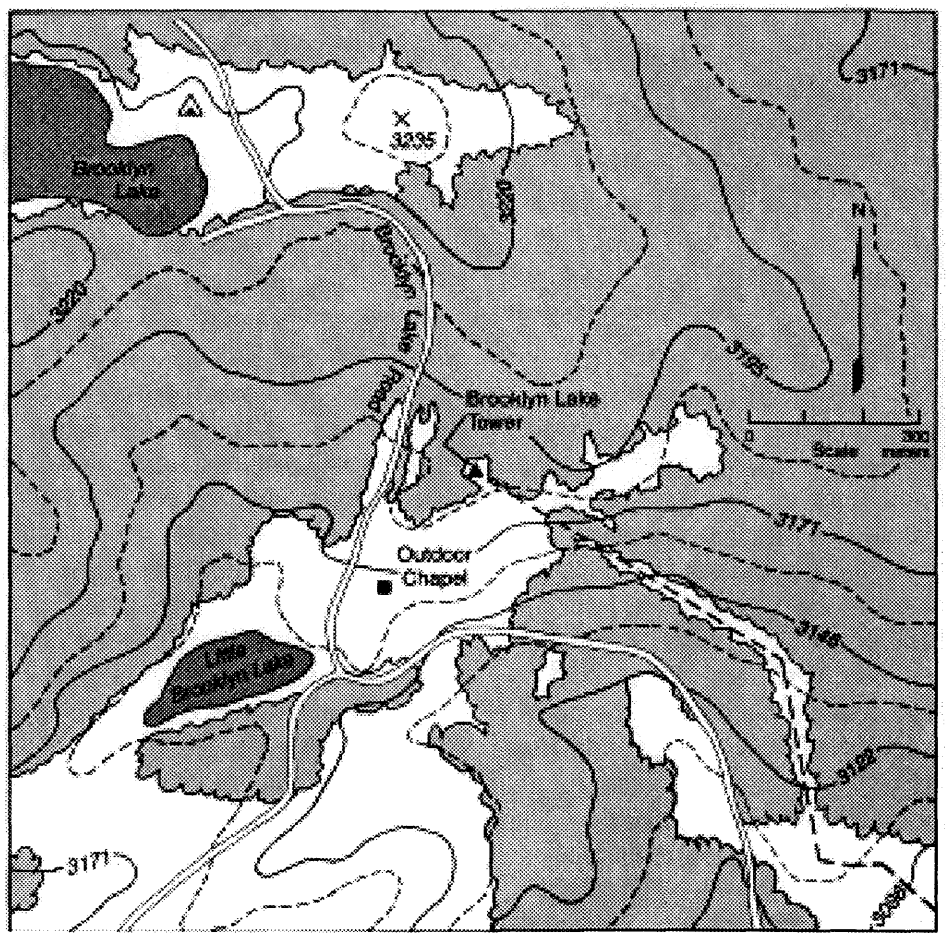

Figure 1.—Plan view of GLEES Brooklyn Lake tower site, terrain (elevation in meters, shaded area: forested).

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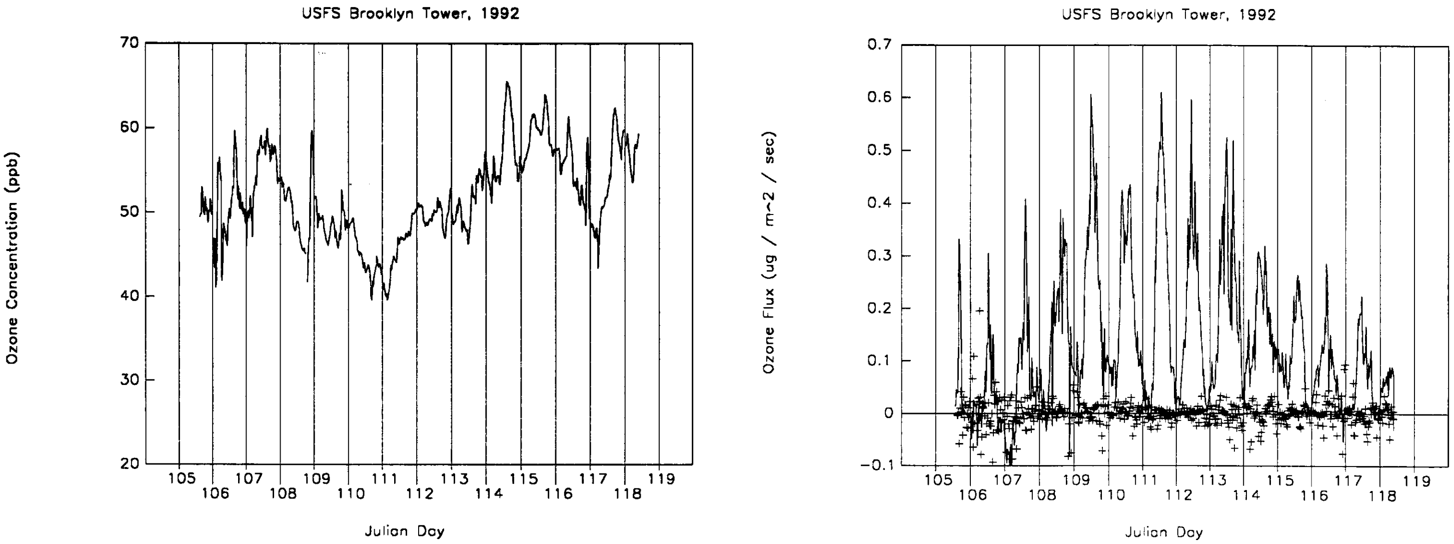

Figure 2.—Ozone concentration and deposition flux for April 14-27, 1992 (Julian day (JD) 106-117).

lyn tower above a subalpine spruce-fir forest (fig. 1.) at the U.S. Forest Service's Glacier Lakes Ecosystem Site (GLEES) [Zeller & Hehn, 1994). Ozone concentrations at GLEES average from 45 to 60 ppb year round [Musselman et al., 1992; Wooldridge et al., 1994], and are typical of high altitude rural sites [Wunderli and Gehrig, 1990]. However upward fluxes as large as 0.5 µg m^{-2} s^{-1} were measured during the 1991-92 winter season. These values, equivalent to 10.8 kg km^{-2} day^{-1}, are similar to the peak summer 1992 growing season downward fluxes measured at the same location.

Figure 2 shows the day-to-day consistency of the upward O_3 fluxes for several days. Half-hour average (a) O_3 concentration in parts per billion (ppb) and (b) O_3 flux (lines) and vertically integrated time rate of O_3 change (+) in micrograms per square meter per second (µg m^{-2} s^{-1}) for the period April 14 to 27, 1992. Temperatures ranged from 5 °C to -10 °C during this period. Ozone fluxes exceeded 0.5 µg m^{-2} s^{-1} and deposition velocities ranged from -0.8 to 0.2 cm s^{-1}

Figure 3 covers the period snowmelt ended and the daytime O_3 flux direction switched from upward to downward. Ozone fluxes ranged from positive to negative on any day during this period but remain predominately negative after JD 138. Half-hour

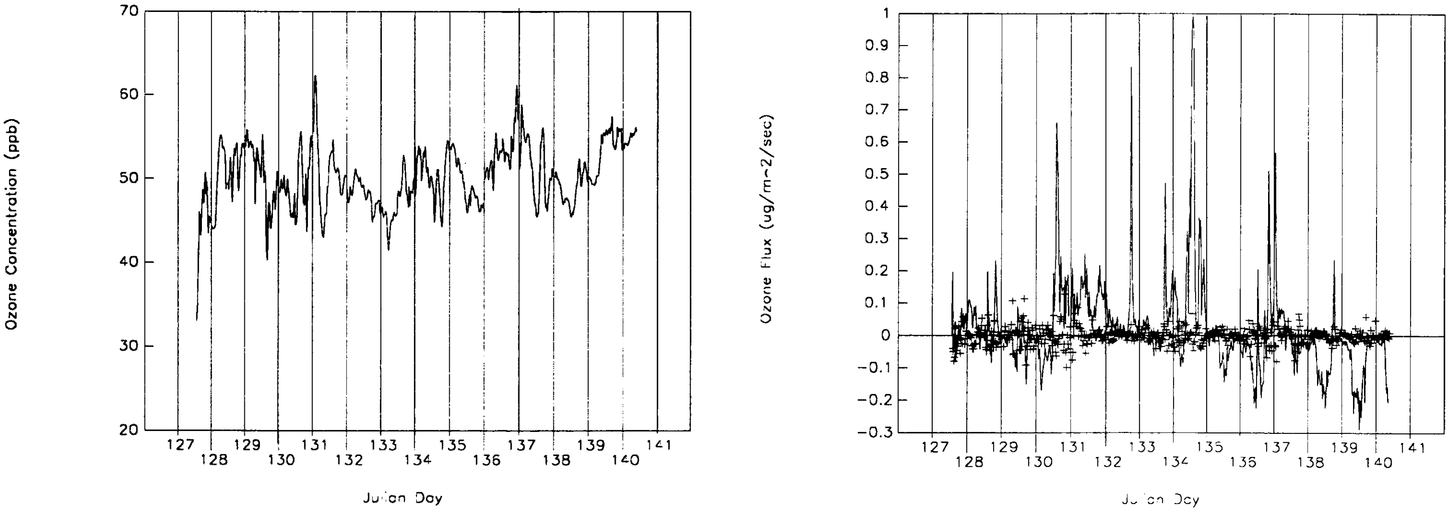

Figure 3.— Ozone concentration and deposition flux for May 6-19, 1992 (JD 127-140).

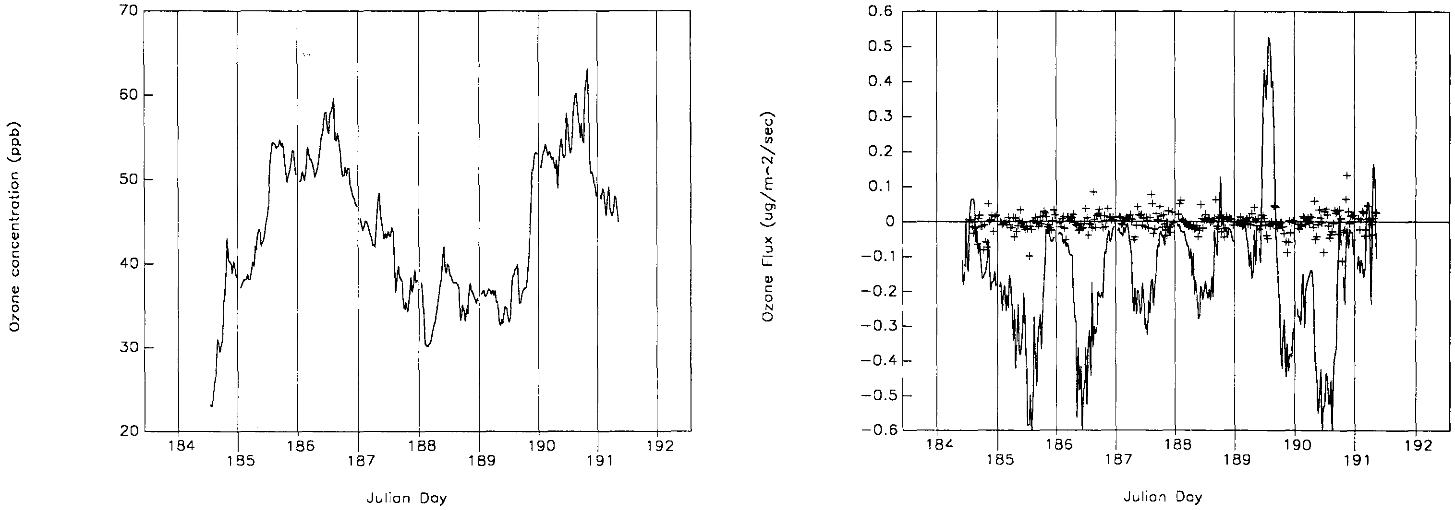

Figure 4.—Ozone concentration and deposition flux for July 2-9, 1992 (JD 184-191).

average (a) O_3 concentration in parts per billion (ppb) and (b) O_3 flux (lines) and vertically integrated time rate of O_3 change (+) in micrograms per square meter per second (mg m^{-2} s^{-1}) for the period May 6 to 19, 1992. Temperatures ranged from 3° to 10 °C above zero except for a brief nighttime excursion below freezing on JD 131. Deposition velocities also peaked at -1.5 cm s^{-1} on JD 131 but generally ranged from -0.4 to 0.3 cm s^{-1}.

Figure 4 shows the typical negative O_3 fluxes that occur during the summer growing season. The downward diurnal flux pattern is briefly interrupted on JD 189 when it rained 0.3 mm. Half-hour average (a) O_3 concentration in parts per billion (ppb) (b) and O_3 flux (lines) and vertically integrated time rate of O_3 change (+) in micrograms per square meter per second (mg m^{-2} s^{-1}) for the period July 2 to July 9, 1992. Temperatures during this period ranged from 5 to 18 °C but remained below 7 °C on JD 189. Deposition velocities during this period ranged from -0.37 on JD 189 to 0.4 cm s^{-1}.

Figure 5 shows the transition from negative daytime O_3 fluxes to positive fluxes. During this period, temperatures dropped near to below 0 °C and RH increased from 30 to 80% at the same time O_3 fluxes turned positive. Although snow depth records were not taken at this time, based on the meteorological data it is most likely that snow

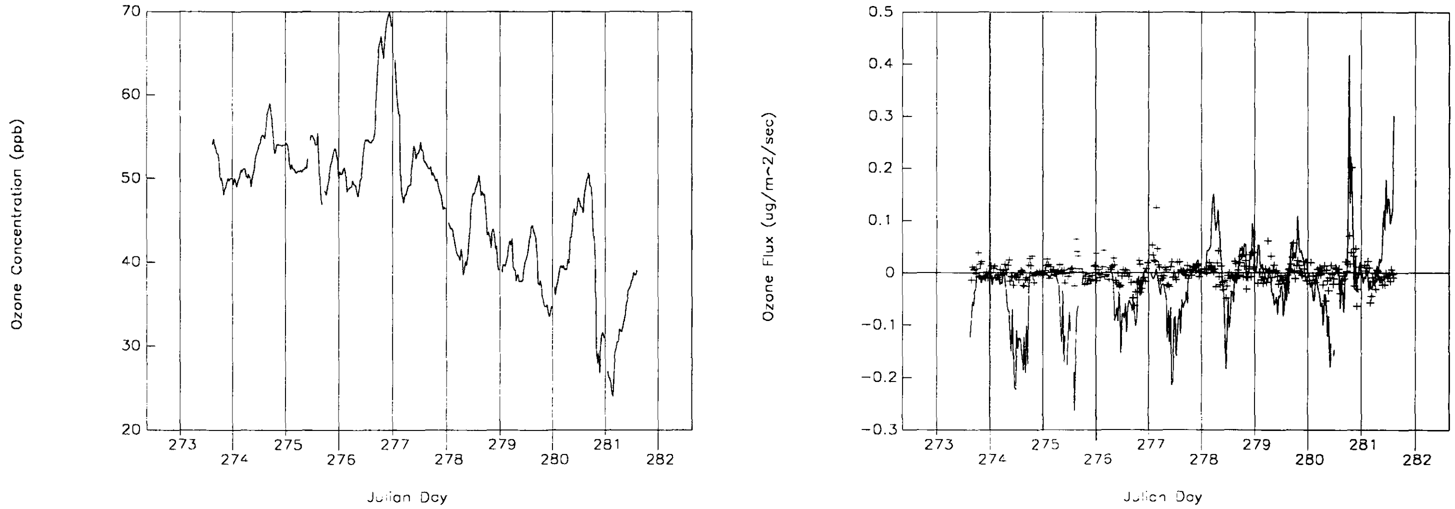

Figure 5.—Ozone concentration and deposition flux for September 29-October 8, 1992 (JD 274-281).

flurries started JD 278 and snow started accumulating on the ground by JD 279. Half-hour average (a) O_3 concentration in parts per billion (ppb) and (b) O_3 flux (lines) and vertically integrated time rate of O_3 change (+) in micrograms per square meter per second (mg m^{-2} s^{-1}) for the period September 30, 1992, to October 7, 1992. Prior to JD 278 daytime temperatures ranged from 7° to 15 °C then dropped to between 0° to 5 °C and finally dipped below freezing on JD 280. Deposition velocities ranged from -0.5 to 0.3 m s^{-1} during this period.

Ozone Below Tree Canopy

Ozone fluxes were measured by eddy correlation below and adjacent to the *Picea engelmannii* (48%), *Abies lasiocarpa* (48%), *Pinus contorta* (4%) canopy at 1-2 m height in an open meadow site in the Snowy Range Mountains of Wyoming during 1994. The measurements were made in April over 2 m deep snow cover, in June at the end of spring melt over saturated soil with very little vegetation and in August over full summertime vegetation. Results show that O_3 flux is consistently downward: -0.01 ±0.009 μm^{-2} s^{-1} above the snow-air interface, increasing to -0.25 ±0.07 μm^{-2} s^{-1} by the end of spring melt, and -0.35 ±0.09 μm^{-2} s^{-1} above the full-growing meadow canopy. Daytime surface O_3 uptake resistance values over snow at this site were between 40 and 80 s cm^{-1}, higher than above-snow resistances reported elsewhere. The snow surface in a deep-snow, subalpine environment, provides a minimal sink for O_3. The 1994 meadow measurements show consistent downward O_3 fluxes that increase dramatically and change diurnal patterns with change in season . Diurnal O_3 concentration patterns also change from winter to summer corresponding to changes in O_3 deposition. The April-May 1994 flux measurements associated with snow cover provide for very large O_3 surface resistances.

In figure 6a, the winter sample period experienced a diurnal concentration variation of about 4 ppb. The average maximum daily values change little by the end of spring melt, however the diurnal variation increased to about 14 ppb because of nighttime decreases in O_3 concentration. This day-night variation increased to about 20 ppb by the August period. Average diurnal changes and standard deviations in (a) O_3 concentration; (b) O_3

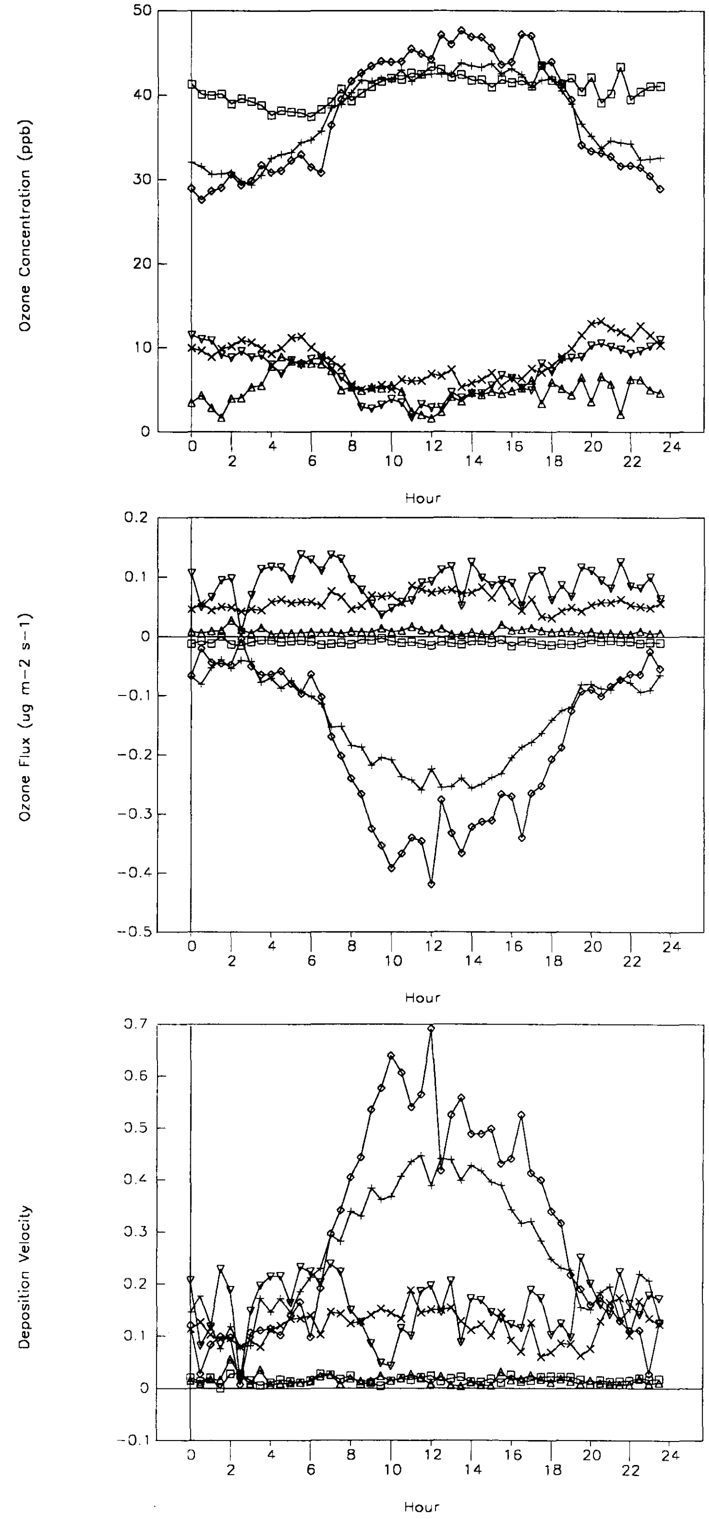

Figure 6.—(a) The diurnal O_3 concentration averages and standard deviations (TECO49 data) for each of the three periods; (b) for each of the three periods, seasonal changes in dirunal ozone flux corresponding to the concentration patterns shown in figure 6.a; (c) the diurnal average O_3 deposition velocities (in cm s^{-1}) for each of the three periods.

deposition flux; and (c) O_3 deposition velocity for April 24-May 3, 1994 (❑ average, Δ standard deviation); June 7-21, 1994 (+ average, × standard deviation); and August 2-10,1994 (◊ average, ∇standard deviation).

During the April 24-May 3 (fig 6b.), period fluxes averaged about $-0.01 \pm 0.009\ \mu g\ m^{-2}\ s^{-1}$ with no diurnal variation. These values are about 35% smaller than fluxes measured over aged snow a few cm depth in a prairie grassland ecosystem 150 km southeast of the GLEES area (Stocker et al., 1995). By the end of snow melt, June 7-21, a well developed diurnal deposition wave emerged with maximum average daytime fluxes of $-0.25 \pm 0.07\ \mu g\ m^{-2}\ s^{-1}$. The meadow during this period was flooded with a few cm of surface runoff water by midday. Vegetation at this time was limited to the previous season's dead compacted grasses, herb, and shrub stems including a few shoots of new growth toward the end of the period. The August 2-10 period shows summertime O_3 fluxes increasing at a faster rate in the morning and achieving greater midday values, $0.35 \pm 0.09\ \mu g\ m^{-2}\ s^{-1}$ because of additional O_3 uptake by plant respiration and the added leaf surface area. Deposition can be further parameterized through the simple resistance analogy [eq. 1].

$$V_d = 1/(r_a + r_c) \qquad (1)$$

Here r_a is atmospheric resistance and r_c total surface resistance. Daytime r_c values for O_3 ranged between 40 to 80 s cm^{-1} for the April 24-May 3 period, 2.5-3.5 s cm^{-1} for June 7-21, and 2-3 s cm^{-1} for August 2-10. The winter scenario r_c values compare to 23 s cm^{-1} over aged snow and 8 s cm^{-1} over new snow report by Stocker et al. (1995) for a grassland ecosystem and 35 s cm^{-1} over a completely snow-blanketed northeastern Illinois field site (Wesely et al., 1981). The snow in the Brooklyn Lake meadow during this period would classify as aged snow.

Carbon Dioxide and Carbon Dioxide Fluxes

Carbon Dioxide Below Tree Canopy in Open Meadow

Seasonal ambient eddy correlation carbon dioxide (CO_2) flux measurements were made utilizing a sonic anemometer and an in-situ open-path fast response infrared gas CO_2 analyzer. These measurements (fig. 7) were taken at 1-2 m height above the wet sub-alpine meadow (grass canopy). Significant changes in seasonal diurnal CO_2 vertical flux patterns were observed. During the growing season the diurnal cycle of CO_2 fluxes were downward during daylight and upward at night as expected because of photosynthesis and respiration. In winter, 1-2 meters above the snow surface at the same location, CO_2 fluxes were upward during daylight (fig. 8), exactly opposite to the growing season observations, and zero at night. These upward fluxes signify CO_2 emissions with measured values of 0.36 mol $m^{-2}\ d^{-1}$. Simultaneous measurements of atmospheric turbulence and CO_2 concentrations show that air turbulence is the primary mechanism for vertical CO_2 transport above the air/snow interface in winter. Night time ambient CO_2 concentrations at 1 meter increased 2 to 3% above background levels when wind speeds are relatively calm indicating that CO_2 is still emitted from the snow but not rapidly dispersing upward. The 1991 winter time CO_2 emission estimates based on measured CO_2 gradients within the snow, diffusion coefficients and an average snow porosity at a snow-covered location, in a forested opening 100 meters east of the CO_2 eddy correlation measurement site, have been calculated and reported to be as high as 0.137 mol $m^{-2}\ d^{-1}$, one third the measured CO_2 emissions presented here.

Conclusions.

Ozone Above Tree Canopy

The O_3 flux data measured by eddy correlation at the GLEES Brooklyn tower, Snowy Range, Wyoming, show reasonable summer growing season deposition (-0.5 mg $m^{-2}\ s^{-1}$) and deposition velocity (0.4 cm s^{-1}). During winter and nongrowing seasons, upward O_3 fluxes were measured. The late winter upward fluxes are the same magnitude as the summer downward fluxes, and V_d's frequently approached -0.9 cm s^{-1}. As O_3 does not readily deposit on snow, the measured rate of O_3 deposition is expected to decrease during the winter but not reverse direction. The flux directional transition is apparently seasonal. The explanation for the upward O_3 fluxes remains unknown but suggest either: (1) some unknown source of O_3 below the 23-meter measurement height; or (2) some other mechanism affecting local O_3 fluxes: three possibilities were presented here.

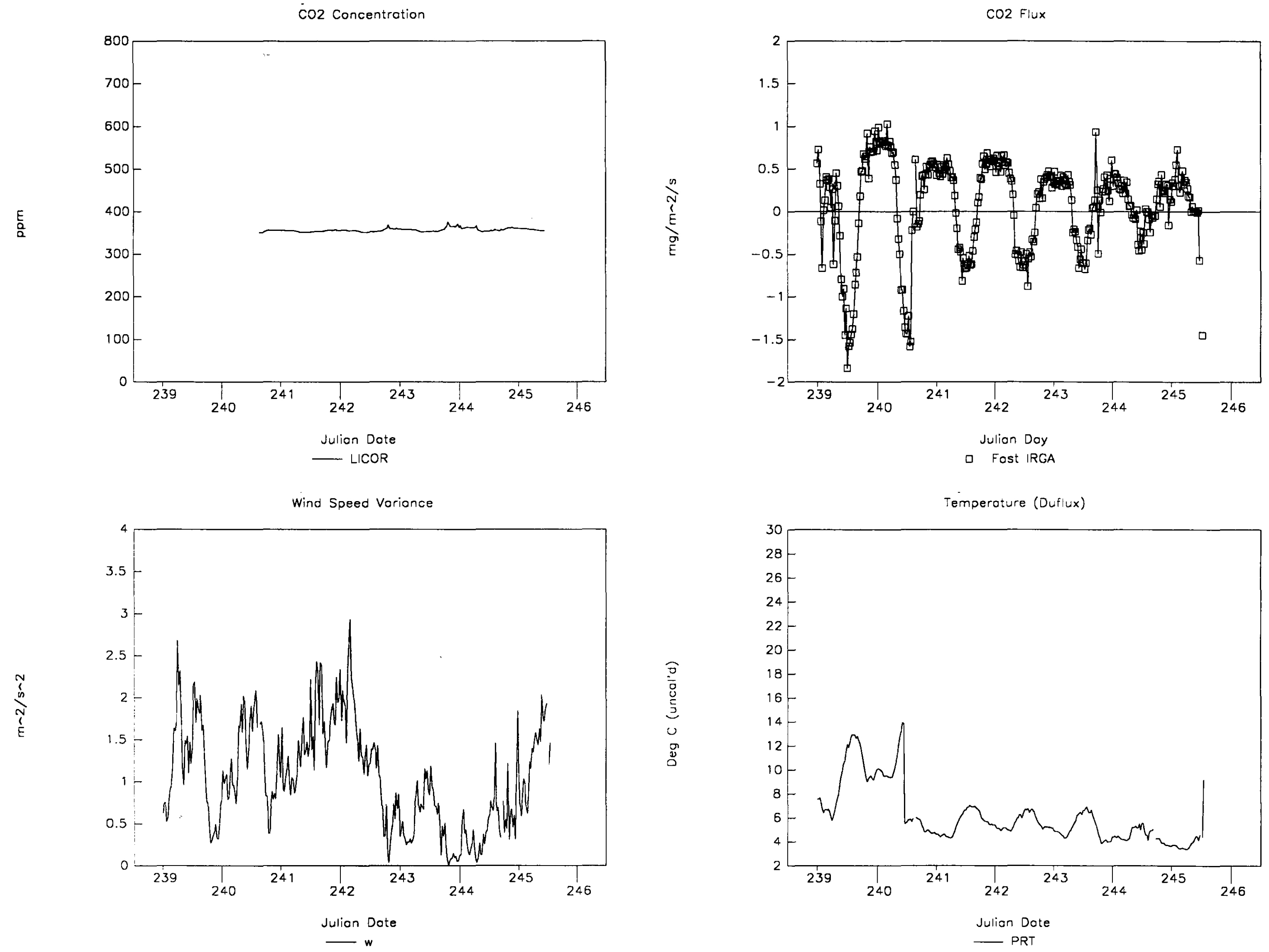

Figure 7.—The average CO_2 concentration, CO_2 flux, vertical wind speed variance, and temperature for a 7-day period in August 1992. Note daily CO_2 cycle appears to respond to the daily temperature and vertical wind variance cycle.

Ozone Below Tree Canopy in Open Meadow

Ozone deposition to deep snow in a rural subalpine meadow environment is consistently downward but very slow: -0.01 ±0.009 m m^{-2} s^{-1}. In the absence of both snow and active vegetation, O_3 deposition increases to -0.25 ±0.07 m m^{-2} s^{-1}. Over an actively growing grass-herb-shrub wet subalpine meadow, average daytime fluxes are -0.35 ±0.09 m m^{-2} s^{-1}. Daytime surface O_3 uptake resistance over deep snow can be 40 to 80 s cm^{-1}, demonstrating that the snow surface in a relatively deep-snow (2 m), subalpine environment, provides a minimal sink for O_3.

Carbon Dioxide Below Tree Canopy in Open Meadow

Carbon Dioxide fluxes measured in the Brooklyn wet meadow site demonstrate normal diel cycles during the summer growing season. During the winter, however the meadow site appear to be a net CO_2 producer

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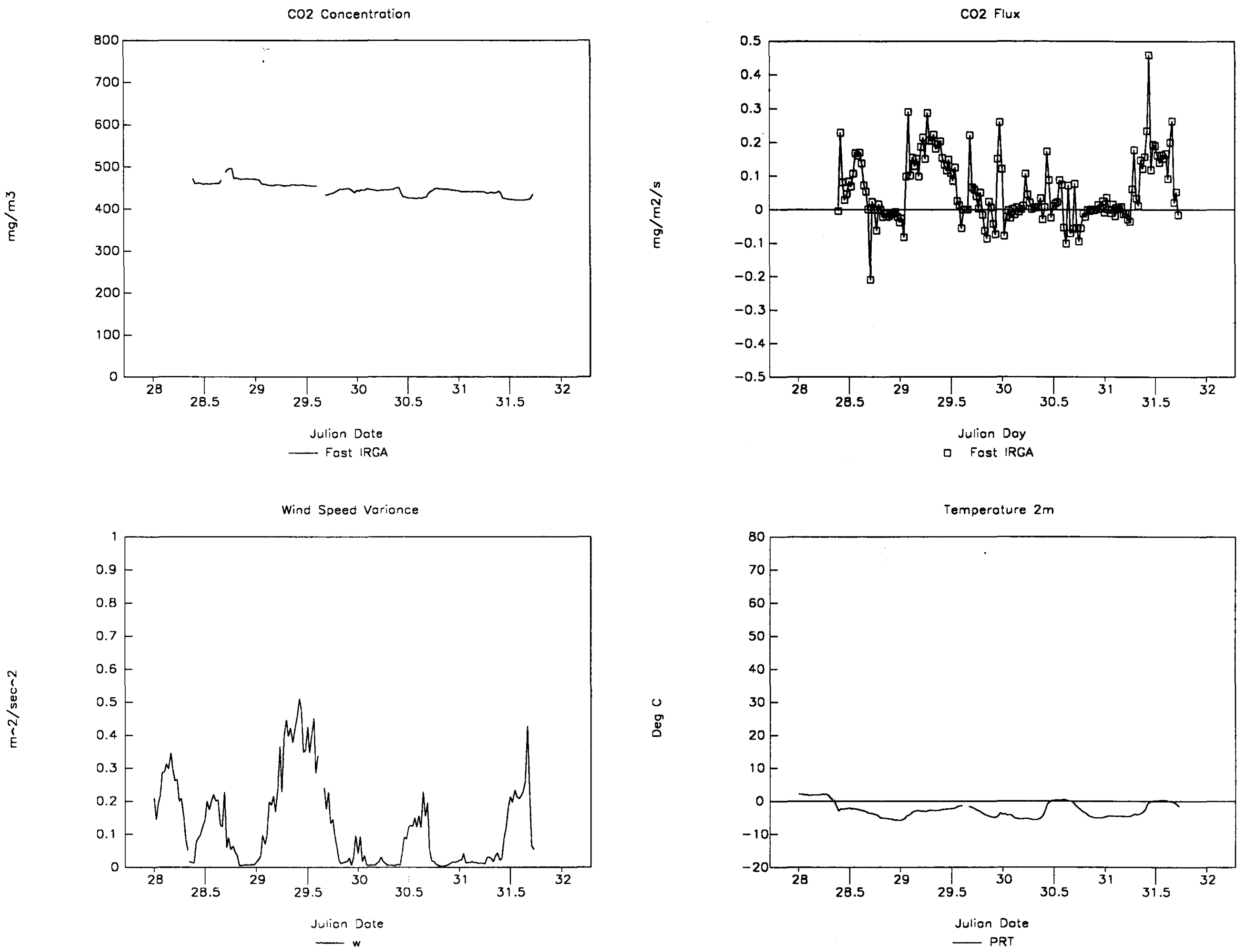

Figure 8.—The average CO_2 concentration, CO_2 flux, vertical wind speed variance and temperature during a 4-day period in January 1993. Note daily CO_2 cycle appears to respond to the daily wind variance for this wintertime scenario.

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