3.10 NOCTURNAL AIR DRAINAGE IN FOREST CANOPIES: A NEW WAY OF STUDYING PHYSIOLOGICAL RESPONSES TO THE WEATHER?

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1. INTRODUCTION

There have been many studies of nocturnal air drainage flow on slopes because of its importance in determining the microclimate of the slope and the landscape below. Under clear skies with weak synoptic flow, radiative cooling at night generates drainage flow even over very shallow slopes (Mahrt, Vickers et al. 2001). Over steeper slopes, drainage flow generates the katabatic winds that are a major ventilation system of mountain regions at night in otherwise calm, clear conditions. The majority of observational studies of drainage flow have focused on understanding the temperature and wind fields on relatively steep slopes (e.g.(Bergen 1969: Horst and Doran 1986: Manins and Sawford 1979: Yoshino 1975)), but recently there has been interest in quantifying advection of carbon dioxide, water vapor and heat in nocturnal drainage flow to improve interpretation of vegetation-atmosphere exchange measured by eddy covariance methods. (Aubinet, Heinesch et al. 2003: Staebler and Fitzjarrald 2004).

The requirements for eddy covariance flux studies dictate that measurements are made at almost horizontal sites. But many natural ecosystems grow on steep slopes, and it would be attractive to have methods for studying vegetation-atmosphere exchanges in these situations. Drainage flow in steep valleys appears to offer such an opportunity because the watershed contributing to the exchange is defined clearly by the topography. This raises the possibility of using measurements of the horizontal flux at the base of a valley to quantify rates of emission of trace gases from the ecosystem in the valley. In particular, at night, ecosystems respire carbon dioxide (CO_2) from foliage, branches and stems, living roots, and decaying organic matter. This flux of CO_2 is not only an important component of the carbon budget of the ecosystem, valuable for quantifying in its own right, but it also contains information about recent photosynthesis and the factors controlling it. For example, Hogberg et al. (2001) showed that soil respiration (which often accounts for more than 70% of forest ecosystem respiration) was strongly influenced by recent photosynthesis. And Bowling et al. (2002) found that when photosynthesis was restricted by plant responses to large vapor pressure deficits or dry soils, ecosystem respiration became enriched in the heavy stable isotope of carbon (^{13}C).

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We therefore hypothesize that measurements of the CO_2 concentration and carbon isotope ratios in air flow draining from a well-defined valley watershed at night can be combined with wind speed and other microclimate information to monitor seasonal and interannual variations in ecosystem metabolism at the watershed scale. This paper describes some preliminary measurements in a forested watershed to test our hypothesis.

One of the challenges in interpreting the measurements concerns the structure of the drainage flow and its interaction with air above the flow. Most studies of valley drainage flow have been conducted in landscapes with sparse vegetation. In such situations, radiative cooling generates the lowest temperatures at the ground, and the drainage flow is often stably stratified with maximum velocity close to the slope surface (Mahrt 1986). The principal force generating the flow is the (negative) buoyancy term associated with cooling near the surface; drag at the ground and the rate of turbulent transfer of momentum at the upper boundary of the flow are often the main opposing forces (Mahrt 1982: Manins and Sawford 1979). When slopes are covered with dense vegetation, the structure of drainage flow is more complex. The canopy top is the source of radiative cooling to the night sky. As air cools near the canopy top it may generate a stably stratified above-canopy drainage flow, similar to that on bare slopes but displaced upwards. Komatsu et al. (2003) reported that this form of flow was quite common over a tropical forest when wind speeds were low at night.

Nocturnal air flow within the canopy on steep slopes has seldom been studied. The aerodynamically rough canopy creates frictional drag on the above-canopy flow and generates turbulence that may mix air into the canopy air space, although strong thermal stability associated with the canopy-top inversion inhibits turbulence persistence. The vertical gradient of air density associated with cold temperatures at the canopy top allows air to subside into the canopy. Down-slope gravity flow in the canopy air space is therefore likely, but the temperature stratification is likely to be very different from that over bare slopes, and the frictional drag imposed by foliage, limbs and tree stems will generate a wind profile unlike classic drainage flow. For these reasons it has been surmised that in-canopy flow would probably be weak and shallow, and isolated from flow above the canopy by the temperature inversion at the canopy top (Mahrt 1986).

Principles of continuity require that, if drainage flow accelerates and deepens on its way down the watershed, there must be entrainment of scalars and momentum at the top of the flow. In studying in-canopy air flow in a forested watershed, quantifying the entrainment flux of carbon dioxide from air above the canopy, which dilutes the concentration attributable to respiration, is a critical part of applying drainage methods for ecosystem CO_2 flux determination.

In this paper we address three questions concerning the air drainage in a steep, forested valley:

- How does the vertical structure of wind speed and temperature in the forest canopy vary during the day and seasonally?
- How is the carbon dioxide concentration in the canopy air space influenced by properties of the drainage flow?
- Can the advected mass flow of carbon dioxide in air draining from the valley be related to ecosystem respiration and free-air entrainment?

2. SITE, METHODS AND INSTRUMENTATION

Our study site is a watershed of about 112 ha, defined by a deeply incised valley, in the H.J. Andrews Experimental Forest, a long-term ecosystem research site in the western Cascade mountains of Oregon. The axis of the V-shaped valley descends in a roughly northwesterly direction (320°) from a ridge top at about 1010m to the valley base at 430m over a distance of about 1400m, giving a mean gradient of about 40%. The old-growth forest covering the watershed was harvested in the 1960’s, and it is now covered by a vigorous second-growth forest of predominantly Douglas-fir with a mean height of about 24m.

To study the cold air drainage flow we erected a triangular-profile tower 28m high at the base of the watershed where the valley is steep-sided and narrow. The tower extended about 4m above the canopy. Wind speed and temperature was measured at eight levels on the tower using sensitive cup anemometers (Thornthwaite, Met One), two-dimensional sonic anemometers (Vaisala), and thermistor temperature probes in radiation shields (Campbell Scientific). Wind direction was measured at three levels, and a net radiometer (Campbell Scientific) was deployed at the top of the tower. Figure 1 shows the arrangement of the instrumentation. Signals were measured every second and averaged over either 1 minute (sonic anemometers) or 15 minute intervals (all other) meteorological instruments).

Continuous measurements from these instruments began in May 2003. On several days, profiles of CO_2 concentration were measured on the tower by drawing air for 2 minutes sequentially from each instrument sampling height (see fig. 1) into an infrared gas analyzer (LICOR 6262). Prior to monitoring the CO_2 concentrations the air was drawn through the pump for 1 minute to evacuate the sample lines. The measurements for each height were averaged over half-hour intervals to generate vertical profiles. Samples of air were also collected in 20ml vials at intervals through the night during these campaigns for subsequent analysis in the laboratory for carbon isotopes.

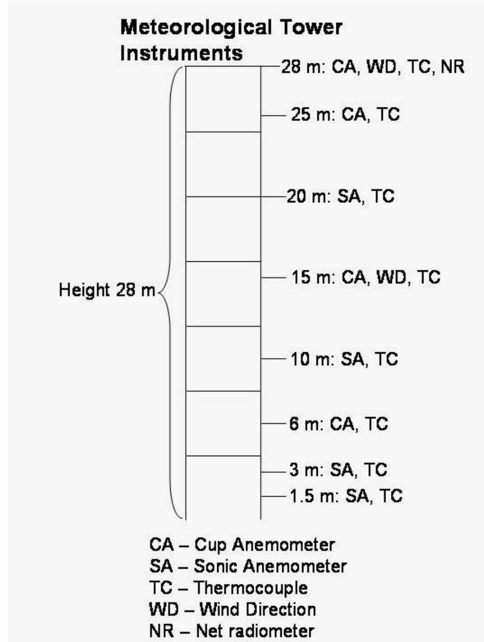

Figure 1: Schematic of arrangement of instrumentation on the tower.

3. RESULTS

In-canopy air flow down the valley (from wind directions 90-135°) occurred on most nights in summer, but was less frequent in fall when skies were more often cloudy and synoptic winds were stronger. During the day, wind direction in the canopy was usually up-slope from about 0800 to 1600 in summer. Figure 2 shows that the down-slope flow was observed at all heights where direction was recorded. The shape of the vertical wind speed profile was consistent below about 15m throughout the year, and the peak wind speed observed at around 5m was also remarkably constant (Figure 3). Contrary to expectations, the drainage flow extended throughout the depth of the canopy, though the strongest flow was in the trunk space. Lower wind speeds above 15m are probably caused by frictional drag of foliage which is mainly in the 15-24m layer. It is not possible to draw any conclusions about the shape of the wind profile above the canopy (the tower will be extended in 2004 for such investigations) but the wind speed differential between 25 and 28m became consistently larger with time over the period July to December. Downslope wind speeds in the canopy were usually at their maximum close to sunset, then declined for the remainder of the night. (Figure 4).

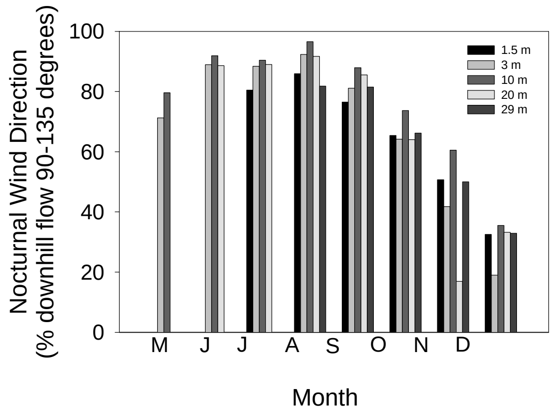

Figure 2. Percentage of time from May to December 2003 when nocturnal air flow was down the valley.

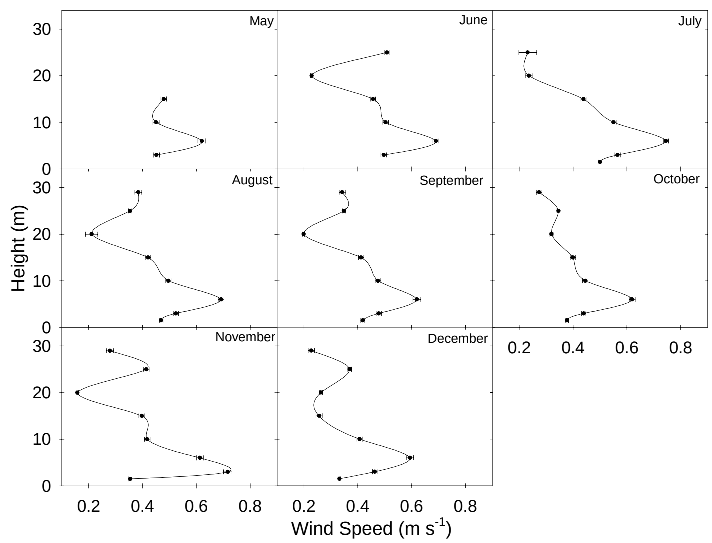

Figure 3. Monthly mean vertical profiles of nocturnal wind speed in 2003.

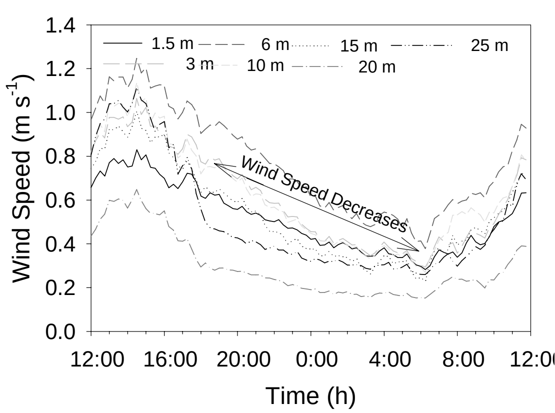

Figure 4. Mean variation during August 2003 of wind speed with time at seven heights within and above the canopy.

The vertical profile of temperature in the canopy varied throughout the day in a well-defined manner. Figure 5 shows the August mean daily variation of potential temperature at seven heights. From about 0700 to 2000 PDT the warmest temperatures were at 25m, close to the upper foliage layer where most solar radiation was being absorbed. During the morning, temperature increased most rapidly at the highest measurement level, reaching a maximum at about 1500. Temperatures lower in the canopy peaked slightly later. From 0700 to early evening the temperature profile in the canopy was stable. After about 1800 PDT in summer, temperatures near the top of the canopy declined rapidly as the net radiation at the canopy top became negative, while temperatures near the ground declined more slowly. The falling temperature at the canopy top created a thermal inversion, with neutral to unstable conditions inside the canopy. Consequently, the air draining downslope within the canopy became very well mixed by about 2000, with the potential temperature profile isothermal; this well-mixed regime persisted until about 0700 the next morning, with mean potential temperature decreasing by about 0.6°C per hour.

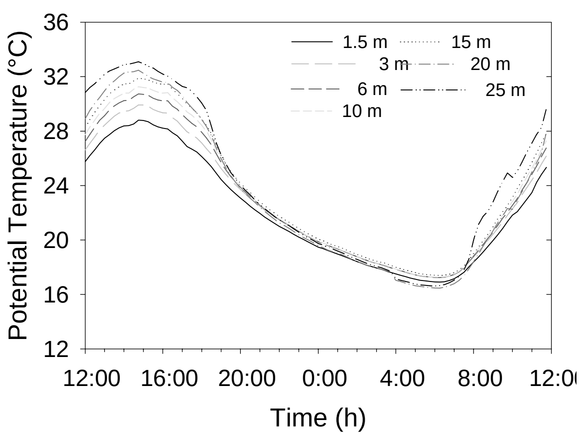

Figure 5. Average variation in August 2003 of potential temperature with time at seven heights in the canopy.

Figure 6 shows a typical example of the variation of CO_2 concentration with time at several heights in the canopy. During the daylight hours, from 1600 to 2000 PDT on 5 August and then from about 0700 to 1500 on 6 August, the concentrations were very variable but concentration at 3m was largest, consistent with the large source of respired CO_2 below the surface. Concentrations near the canopy top were close to background for this region, about 360ppm. After 2000 PDT, when the canopy air space became well mixed, the CO_2 concentration was independent of height, and increased at about 4.5ppm per hour until sunrise around 0500. After sunrise, the canopy air remained well mixed for about 2 hours while CO_2 concentration decreased.

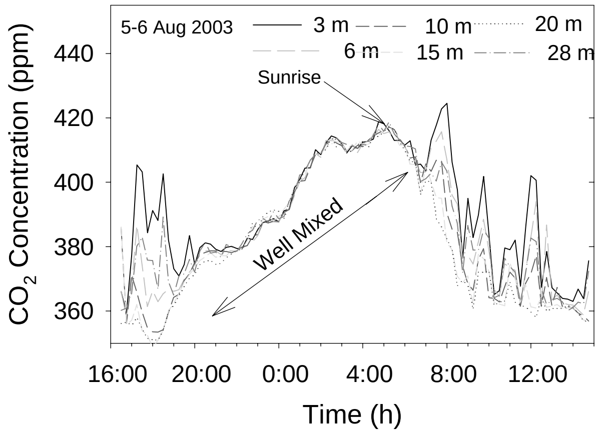

Figure 6. Variation of carbon dioxide concentration with time at several heights in the canopy on 5-6 August 2003.

The strong association between temperature and carbon dioxide gradients is illustrated in Figure 7 which shows that temperature gradients between 3m and 28m decreased rapidly to close to zero around 2000, and the CO_2 gradient between the same levels responded similarly; after about 0700 on 6 August the daytime stratification of temperature and CO_2 concentration was re-established.

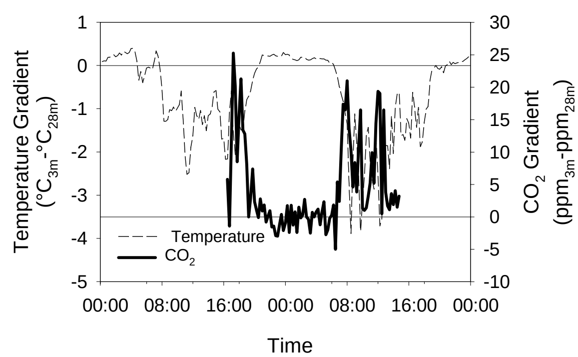

Figure 7. Variation with time of the gradients of temperature and CO_2 concentration between 3m and 28m on 5-6 August 2003.

4. DISCUSSION

Nocturnal cold air drainage down this steep, forested valley is common, particularly in summer when the combination of clear skies and low synoptic wind speeds is frequent. Contrary to expectations, the nocturnal in-canopy drainage flow is deep, rapid moving, and usually well-mixed (Figures 3-7). The flow velocity declines during the night (Figure 4). This may be an indication of entrainment of heat by turbulent transport from above the drainage flow, reducing the buoyancy force driving the flow. Alternatively it might indicate the 'damming effect' of a pool of cold air accumulating at the base of the watershed and generating hydrostatic pressure to slow the flow. The rate of cooling of air in the canopy (~0.6°C h^{-1}) during the well-mixed phase corresponds to a net sensible heat loss in the system of about 6 W m^{-2}.

As the drainage wind speed decreased during the night, the CO_2 concentration increased (Figure 6). Thus the output flux of CO_2 in air draining from the watershed varied less than the factors determining it, but a rough estimate demonstrates that the flux was not constant with time. To estimate the output flux of CO_2 from the watershed, we assumed that the wind speed and CO_2 concentration measured at each height on the tower also applied at the same height across the cross-section of the valley. We treated the flow through the cross-section of the valley passing through the tower as occurring in 6 layers (0-3,3-6,6-10,10-15,15-20, and 20-25m). For each layer *i* we calculated the mean measured wind speed u_i and CO_2 concentration C_i using 15 minute data. We approximated the valley cross section as a rectangle 5m wide by 3m high for the first layer, then as a trapezoid with the valley sides sloping at 33° to the horizontal. Then the output flux F_o of CO_2 is given by

$$F_o = \sum_{i=1}^{6} C_i u_i A_i$$

where A_i is the cross-sectional area of layer *i*.

Figure 8 shows the result of this calculation, indicating that the output flux decreased with time until about 0200. The increase after this time may indicate increased turbulence above the canopy of the type reported in a stably stratified nocturnal boundary layer by Blumen (1984) and Nakamura and Mahrt (in press).

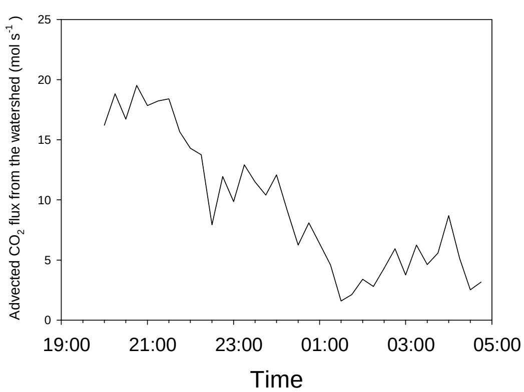

Figure 8. Carbon dioxide flux leaving the watershed in cold air drainage flow, 5-6 August 2003.

An estimate of the ecosystem respiration contributing to the advected flux can be made assuming that ecosystem respiration was 7 µmol CO_2 m^{-2} s^{-1} (Harmon, Bible et al. in press), and that the floor area of the valley was about 112 ha, giving a watershed scale flux of about 8 mol s^{-1}. Mass balance for carbon dioxide in the watershed therefore requires a flux of about 12-0 mol s-1 which is presumably supplied by horizontal and vertical advection of ambient CO_2 into the air mass. The decline in this advected input through the night suggests that it is largely entrainment from the relatively still air above the canopy. The rate of entrainment might be expected to be proportional to the shear across the canopy top, which most likely decreases as wind speed in the canopy declines.

5. CONCLUSIONS

Nocturnal air drainage within the canopy of a steep forested watershed is much stronger and deeper than earlier estimates suggested. The flow becomes well mixed at about the time when net radiation above the canopy becomes negative and a temperature inversion forms at the canopy top. The well-mixed regime persists through the night and into early morning. Measurements of carbon dioxide concentration and isotope ratio characteristic of the entire canopy airspace could therefore be taken simply at one level. Interpreting the relationship between carbon dioxide concentration and ecosystem respiration to develop quantitative mass flux estimates will require better understanding of vertical and horizontal advective transfer in the ecosystem, and such measurements are planned in future years at this site.

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REFERENCES

Aubinet, M., B. Heinesch, and M. Yernaux, 2003: Horizontal and vertical CO_2 advection in a sloping forest. *Boundary-Layer Meteor*., **108**, 397-417.

Bergen, J. D., 1969: Cold air drainage on a forested mountain slope. *J. Appl. Meteor*., **8**, 884-895.

Blumen, W., 1984: An observational study of instability and turbulence in nighttime drainage winds. *Boundary-Layer Meteor*., **28**, 245-269.

Bowling, D. R., N. G. McDowell, B. J. Bond, B. E. Law, and J. R. Ehleringer, 2002: 13C content of ecosystem respiration is linked to precipitation and vapor pressure deficit. *Oecologia*, **131**, 113-124.

Harmon, M. E., K. Bible, M. J. Ryan, D. C. Shaw, J. Klopatek, H. A. Mooney, W. E. Winner, and S. C. Thomas, in press: Production, respiration, and overall carbon balance in an old growth Pseudotsuga/Tsuga forest ecosystem. Ecosystems.

Hogberg, P., A. Nordgren, N. Buchmann, A. F. S. Taylor, A. Ekblad, M. N. Hogberg, G. Nyberg, M. Ottosson-Lofvenius, and D. J. Read, 2001: Large-scale forest girdling shows that current photosynthesis drives soil respiration. *Nature*, **411**, 789-792.

Horst, T. W. and J. C. Doran, 1986: Nocturnal drainage flow on a simple slope. *Boundary-Layer Meteor.*, **34**, 263-286.

Komatsu, H., N. Yoshida, H. Takizawa, I. Kosaka, C. Tantasirin, and M. Suzuki, 2003: Seasonal trend in the occurrence of nocturnal drainage flow on a forested slope under a tropical monsoon climate. *Boundary-Layer Meteor.*, **106**, 573-592.

Mahrt, L., 1982: Momentum balance of gravity flows. *J. Atmos. Sci.*, **39**, 2701-2711.

——, 1986: Nocturnal Topoclimatology. World Climate Applications Program Report WCP-117, 76 pp.

Mahrt, L., D. Vickers, R. Nakamura, M. R. Soler, J. Sun, S. Burns, and D. H. Lenschow, 2001: Shallow drainage flows. *Boundary-Layer Meteor.*, **101**, 243-260.

Manins, P. C. and B. L. Sawford, 1979: Katabatic winds: a field case study. *Quarterly J. of the Royal Meteor. Soc.*, **105**, 1011-1025.

Nakamura, R. and L. Mahrt, in press: A study of intermittent turbulence with CASES-99 tower measurements. *Boundary-Layer Meteor.*

Staebler, R. M. and D. R. Fitzjarrald, 2004: Observing subcanopy CO_2 advection. *Agr. And Forest Meteor.*, **122**, 139-156.

Yoshino, M. M., 1975: Climate in a small area. University of Tokyo Press, 549 pp.