SOIL AND LITTER EVAPORATION BENEATH RE-GROWTH AND OLD-GROWTH MOUNTAIN ASH FOREST

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Preface

The material in this report is a contribution to one of the core research projects in the Cooperative Research Centre for Catchment Hydrology, "Development and evaluation of predictive tools for water production in natural, disturbed and managed forests."

The experiment aims to synthesise our knowledge of forest water balance, to generate key experimental information on the factors that determine how water, soils, trees and landscape interact, and to produce operational models for water productivity that can be used by resource managers and planners.

This report summarises results from one of the intensive experimental phases of the project. The work has been conducted in catchments that supply water to the city of Melbourne, where planning for future water sources is now a matter of intense public debate. The report makes an important contribution to the scientific understanding needed to make the correct resource management decisions.

The reports authorship (David McJannet, Monash University Honours Student; Rob Vertessy, CSIRO, Deputy Director; Nigel Tapper, Sharon O'Sullivan and Jason Beringer, Monash University; Helen Cleugh, CSIRO) reflects the collaboration that is now well developed between CRC participants. That collaboration already extends into other resource agencies who are participating in the research, and who will benefit from it.

Dr Glen Walker
Leader, Catchment Water and Salt Balance Program
Cooperative Research Centre for Catchment Hydrology

Abstract

Microlysimeter and evaporation dome techniques were used to measure soil and litter evaporation (Q_{Es}) in 10 and 235 year old mountain ash forest during five 24 h measurement periods spaced through the year. From the limited measurements, Q_{Es} beneath mountain ash forest appeared to be influenced by forest age. During all but one measurement period Q_{Es} was greater in the 10 year old forest than in the 235 year old forest. The observed dissimilarity is likely to be related to forest structure which is thought to influence energy exchanges and the climate within the forest. During the warmer months Q_{Es} in both the 10 and 235 year old forest is thought to be limited by the availability of moisture, while in the cooler months abundant moisture suggests that energy availability is the limiting factor.

The accuracy of evaporation measurements made by the microlysimeter and evaporation dome techniques was determined through intercomparison with simultaneous evaporation measurements made by micrometeorological techniques. The best agreement between all techniques occurred with low net radiation conditions. This increased the confidence with which the microlysimeter and evaporation dome techniques could be used to measure Q_{Es} in mountain ash forest due to the low net radiation experienced beneath the forest canopy. Although strong agreement was found between the microlysimeter and evaporation dome measurements during comparison in an open field, such agreement was not found when measuring Q_{Es} in mountain ash forest. Possible explanations for the lack of agreement within the forest environment are given.

Combining measurements taken throughout the year, Q_{Es} beneath 10 and 235 year old mountain ash forest translated to estimated water losses of 150 and 110 mm year^{-1} respectively. By combining these values with transpiration and interception rates reported in the literature, Q_{Es} in 235 year old forest was estimated to account for 13% of annual evapotranspiration, while in 10 year old forest it was estimated to account for 14% of annual evapotranspiration.

Acknowledgments

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We wish to thank Russell Wild, Jamie Margules, Jim Brophy, Scott Featherston, Frank Dunin and Allan Wain who provided valuable assistance with fieldwork and Jeff Turner who arranged the construction of the evaporation dome. Melbourne Water kindly provided access to field sites.

We also thank Richard Silberstein and Haralds Alksnis for reviewing the report and Mick Flemming for his valuable advice.

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1. INTRODUCTION

1.1 Background

Mountain ash (*Eucalyptus regnans*) forest dominates 60% of the area of Melbourne's water supply catchments yet yields about 80% of the runoff. (Langford and O'Shaughnessy 1977). These forested catchments, which cover an area of 155 000 ha, yield high quality water which needs minimal treatment to meet the required health standards.

It is predicted that Melbourne's water supply demand will grow at 2-3% per annum over the next 30 years with water supply enlargement necessary by the year 2010 (Duncan 1991a, b). In order to delay the development of expensive water supply infrastructure, research is being conducted with the aim of optimising streamflow from existing catchments. This research is aimed at developing an understanding of the hydrological processes influencing streamflow from the catchments, particularly from ash-type eucalypt forest.

In 1939, bushfires killed about 80% of the old growth forest within Melbourne's water supply catchments. In the years following the bushfire, extensive regrowth was established and it became evident to researchers (Langford 1974, 1976 and Kuczera 1985, 1987) that streamflows from the catchments were declining. This indicated that the water yield from mountain ash forest is related to forest age.

Currently, Melbourne Water and the Cooperative Research Centre for Catchment Hydrology (CRCCH) are carrying out research aimed at predicting the impacts of bushfires, timber harvesting, climate change and natural forest ageing on water yield and more accurately forecasting long term stream flows from the catchments (Vertessy *et al.* 1994). Using extensive field data, the CRCCH is refining the CSIRO Topog model in the hope of eventually developing a model capable of predicting water yield from ash forest at any site and under various types of management regime (CRCCH 1994). The measurements reported in this study are part of a broader objective to measure different water balance components in the mountain ash forest.

1.2 Ecology and hydrology of mountain ash forest

In Victoria, mountain ash forests are confined to the cool mountain regions of the central and eastern highlands. Mountain ash forest usually grows at elevations ranging from 460-1100 m with an average rainfall of 1100-2000 mm (Langford and O'Shaughnessy 1979).

At elevations below 600 m with low rainfall the mountain ash forest is confined to moist, sheltered slopes with southerly aspects while above this level it is found on slopes of all aspects (Cunningham 1960). Bushfires are vital for the natural regeneration of mountain ash forest. The fire not only causes the release of seed from woody capsules in the canopy, but also allows direct sunlight, which is essential for seedling growth, to reach the forest floor. Hundreds of thousands of seeds germinate per hectare and due to intense competition for light, trees grow rapidly. As the weaker trees become shaded out, natural thinning of the stand occurs and continues for the life of the stand at a continuously decreasing rate. As the forest thins out, gaps appear in the canopy and a dense understorey of shrubs, ferns and small trees develops. Without fire mountain ash forest would disappear from a site within 500 years (Ashton 1976). As a result of past fires, the mountain ash forest of Melbourne's water supply catchments are a mosaic of different aged stands.

The importance of fire in the survival of mountain ash forest makes it an important factor to consider in determining catchment responses to disturbance. Fire causes major changes to the structure and composition of the forest which in turn influences site hydrologic processes such as soil evaporation.

Langford (1974, 1976), in his analysis of streamflows from five catchments affected by the 1939 bushfires, found that conversion of ash forest from old-growth to re-growth, resulted in a substantial reduction in catchment water yield. Initial yield increases gave way to sustained water yield decreases once vigorous regrowth became established. Extension and refinement of Langford's analyses allowed Kuczera (1985, 1987) to develop an idealised curve describing the relationship between mean annual streamflow and forest age for ash forest. The so called 'Kuczera curve' (Figure 1.1) has wide error bands which make it difficult to accurately predict when water yields will recover after disturbance. In order to narrow the error bands, a better understanding of the reasons for variation in streamflow with age is required. To date fog drip, rainfall interception, and transpiration have been proposed as causes of the difference in water yield from re-growth and old-growth forest.

Fog drip was discounted as a cause of stream flow changes when the investigations of O'Connell and O'Shaughnessy (1975) showed that it accounted for less than one percent of the gross precipitation and that there was no significant difference in fog drip between re-growth and old-growth ash forest. Interception of rainfall by leaves and branches and eventual evaporation from these surfaces, also could not explain the observed differences in water yield from re-growth and old-growth forests. Langford and O'Shaughnessy

(1978) reported that interception in 34 year old re-growth forest was actually lower than in 160 year old mature ash forest. These authors then proposed that transpiration differences between re-growth and old-growth forest were the cause of stream flow changes.

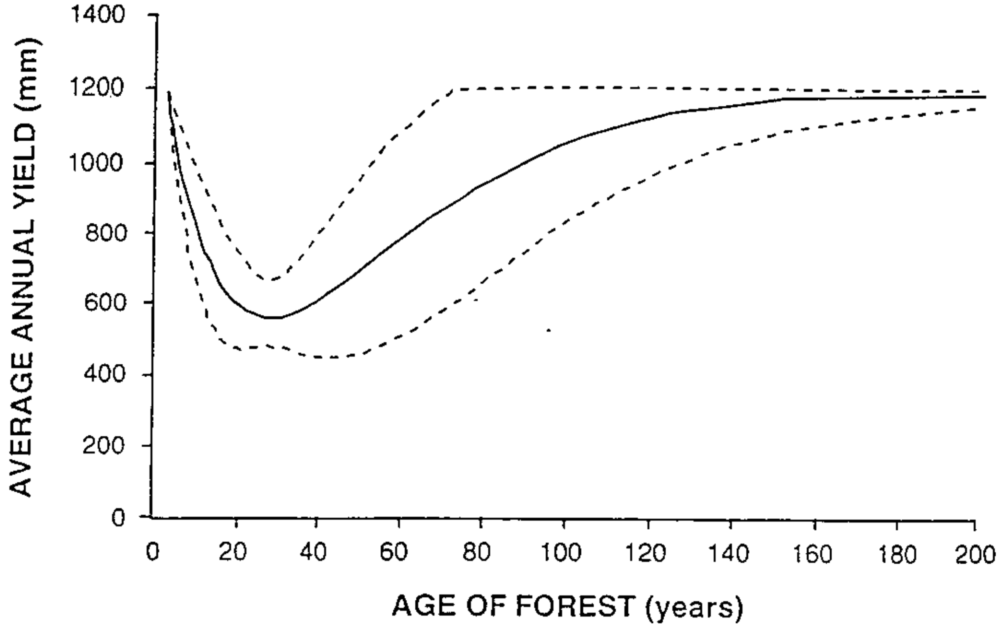

Figure 1.1 Relationship between ash forest age and mean water yield, after Kuczera (1985). The upper and lower curves define the 95% confidence limits.

The first direct measurements of transpiration in mountain ash forest (Legge 1980) found that sapflow velocities were similar in re-growth and old-growth forest. Legge (1980) hypothesised that differences in sapwood area and leaf area were more likely the cause of the relationship between stand age and water yield. Since the work of Legge, heat pulse instruments for measuring sapflow have been developed and used to measure transpiration. Dunn and Connor (1993) used the heat pulse method in 50, 90, 150 and 230 year old mountain ash forest and also found that mean daily sapflow velocities were very similar. They also determined sapwood areas for the four age classes and by combining the sapwood area with sapflow velocities, reported a trend of decreasing water usage with forest age. Dunn and Connor (1993) also measured water use by understorey trees and observed that transpiration of understorey vegetation was much less than that of the overstorey. This supports the findings of Langford and O'Shaughnessy (1979) that understorey vegetation plays a minor role in soil moisture depletion.

Current process studies being carried out by Melbourne Water and the CRCCH in mountain ash forest are aimed at developing a clearer understanding of the causal factors underlying the relationship between forest age and water yield. These studies are looking at age dependent patterns of leaf area, rainfall interception, sapwood area and tree water use (Vertessy *et al.* 1994). Interception studies by Haydon *et al.* (in press) contradict those of earlier investigations which indicated that old-growth forest intercepts more rainfall than re-growth forest. It has now been found that rainfall interception peaks in 30 year old mountain ash forest, which corresponds with the time of minimum water yield suggested by the 'Kuczera curve'. Therefore age dependent changes in interception are consistent with the shape of the water yield versus forest age curve.

Vertessy *et al.* (1995) measured tree diameters, sapwood areas and leaf areas in 15 year old mountain ash forest. They found that tree diameter could explain 93% of the variation in canopy leaf area, 95% of the variation in stem sapwood area and 91% of the daily tree water use. Over the coming years further similar investigations are proposed for different age forests.

The CRCCH is also complementing its process studies in mountain ash forest with the development of a model capable of predicting the water balance of mountain ash forest at different sites and under various types of management regime. A physically based catchment model, which is known as Topog_Yield, has been used within the Myrtle catchments to simulate such things as stand transpiration and interception, catchment yield, and soil evaporation (Vertessy *et al.* 1993). Another model, Topog-IRM, which is a variant of Topog_Yield, has been used in the Picaninny catchment by Vertessy *et al.* (1996) to predict water balance and growth responses of mountain ash forest to clear felling and regeneration. This model was used to simulate throughfall, streamflow, rainfall interception, soil water dynamics and live stem carbon gain over a three year pre-treatment period and a twenty year regeneration period.

The majority of hydrological research in mountain ash forest has focused on processes associated with the forest canopy, such as transpiration and interception, and as yet, little attention has been given to the forest floor process of soil and litter evaporation. Soil and litter evaporation is an important component of the forest water balance and therefore requires further investigation.

1.3 Factors affecting soil and litter evaporation within a forest environment

Soil and litter evaporation from forest floors has received little attention in the literature. Evapotranspiration measurements within forests often ignore evaporation from the soil and litter on the assumption that it is negligible. Although most investigations concentrate on the plant component of evapotranspiration, those that have considered soil and litter evaporation in forest have produced some interesting findings. Kelliher *et al.* (1992), working in New Zealand broad-leaved forest, found that soil and litter evaporation accounted for 10-20% of stand evapotranspiration. Denmead (1984) also found that soil and litter evaporation was important in Australian exotic pine forest and could contribute 10-27% of total evapotranspiration on most days, and up to 40% after rain. Similarly, Lafleur and Schreader (1994) reported that soil and litter evaporation in a Canadian subarctic spruce forest accounted for an average of 30% of the total stand evapotranspiration.

The rate of evaporation in any environment depends on the availability of energy and water, the magnitude of the vapour pressure difference between the evaporating surface and the ambient atmosphere and the efficiency of the transport mechanism (Lee 1978). The difference in vapour pressure between the evaporating surface and the ambient atmosphere is known as the vapour concentration gradient. This gradient is negative if vapour pressure decreases with height, and positive if vapour pressure increases with height. When the gradient is negative, which is usually the case during the day, vapour is transported away from the surface by eddy diffusion. During cool nights it is possible for the vapour concentration gradient to be positive, causing the transfer of vapour towards the surface as dewfall (Oke 1987).

The rate of evaporation from the soil and litter beneath a forest is greatly influenced by the structure of the forest. The structure of a forest is such that the canopy, or active surface, may be quite some distance from the forest floor. The active surface is where most of the drag on airflow is exerted, where much of the precipitation is intercepted, where the majority of the radiant energy is absorbed, reflected and emitted, and where the main transformations of energy and mass occur (Oke 1987).

The drag created by the forest canopy causes a sharp decrease in windspeed down to the level of maximum leaf area. Below the canopy, air motion is normally weak and hence evaporation from the soil and litter can be expected to be lower than in adjacent unforested areas. The extent of windspeed reduction beneath the canopy is determined by the density and height of the stand because of its role in determining surface roughness (Oke 1987).
Rainfall interception by the canopy and understorey vegetation reduces the amount of water received by the forest floor. This in turn influences the availability of moisture for evaporation from the soil and litter. The amount of rainfall intercepted before it reaches the forest floor is also related to the density of the stand.

Humidity within a forest is often higher than in adjacent unforested areas due to the input of water vapour through transpiration from the understorey and canopy, and evaporation from the soil and wet surfaces. Further contributing to the humidity within the forest are the slow windspeeds which limit the transportation of water vapour away from the stand (Stoutjesdijk and Barkman 1987). The amount of water vapour present in the forest air weakens the vapour density gradient between the forest floor and the air above which in turn limits the rate of evaporation from the soil.

The energy available for soil and litter evaporation depends on the characteristics of the canopy and understorey vegetation, as these influence the pattern of incoming and outgoing radiation. Most of the incoming radiation is either absorbed or reflected by the canopy while the remainder reaches the forest floor. This results in cooler daytime soil temperatures compared to unforested areas. Night time temperatures, on the other hand, are found to be greater under forest compared to open areas due to the trapping of longwave radiation which is released from both the forest floor and the canopy. The amount of radiation received by the forest floor varies greatly depending on the type of tree, leaf area index, angle of solar incidence, and canopy height (Barry and Chorley 1982).

According to Oke (1987), the energy balance of the forest, extending from the top of the vegetation to the depth in the soil at which there is no significant vertical heat flux, may be written as:-

$$Q^{*} = Q_H \pm Q_E \pm \Delta Q_S \pm \Delta Q_P$$

Where: -

Q^{*} is the net all wave radiation
Q_H is the sensible heat flux density
Q_E is the latent heat flux density
ΔQ_S is the net rate of physical heat storage

ΔQ_P is the net rate of biochemical energy storage

Physical heat storage changes result from the absorption or release of heat by the air, soil and plant biomass and biochemical energy storage changes result from the process of photosynthesis. This latter term is very small.

Within the forest environment, Q_E is a measure of the amount of energy available for evapotranspiration. Evapotranspiration is the combined loss of water through the processes of transpiration and evaporation from plant surfaces and soil and litter. Transpiration is the process by which water in plants is transferred as water vapour to the atmosphere via the leaf stomates (Oke 1987). In this study, only evaporation from the soil and litter will be measured in the mountain ash forest and will hereafter be given the symbol Q_{Es}.

1.4 Aims of this study

Previous investigations in mountain ash forest (Langford 1974, 1976; Kuczera 1985,1987) have demonstrated that re-growth forests yield less water than old-growth forest. This has been attributed to differences in evapotranspiration. While heat pulse instruments have been used to measure transpiration from the overstorey and understorey (Dunn and Connor 1991; Vertessy *et al.* 1995) and throughfall troughs and rain gauges have been used to determine interception (Langford and O'Shaughnessy 1978; Haydon *et al.* in press), no previous attempts have been made to measure soil and litter evaporation.

Our study is the first to report measurements of evaporation from the soil and litter beneath re-growth and old-growth mountain ash forest. The specific aims of this investigation are:

1. to determine if soil and litter evaporation beneath mountain ash forest is related to forest age;

2. to characterise the seasonal variations in soil and litter evaporation beneath 10 and 235 year old mountain ash forest, and;

3. to estimate the annual rate of soil and litter evaporation beneath 10 and 235 year old mountain ash forest, expressed as a percentage of annual evapotranspiration

The two catchments chosen for this investigation are sited in the North Maroondah experimental area (Figure 1.2). These catchments, which both drain to Myrtle Creek, are named Myrtle 1 and Myrtle 2. Myrtle 1 is dominated by old-growth mountain ash trees of around 235 years of age and heights of up to 80 m. Myrtle 2, on the other hand, was cleared of old-growth forest 10 years ago and has now regenerated with dense mountain ash forest, reaching heights of about 15 m. The forests of these two catchments are very different in structure and investigations will determine if this influences evaporation from the soil and litter layer.

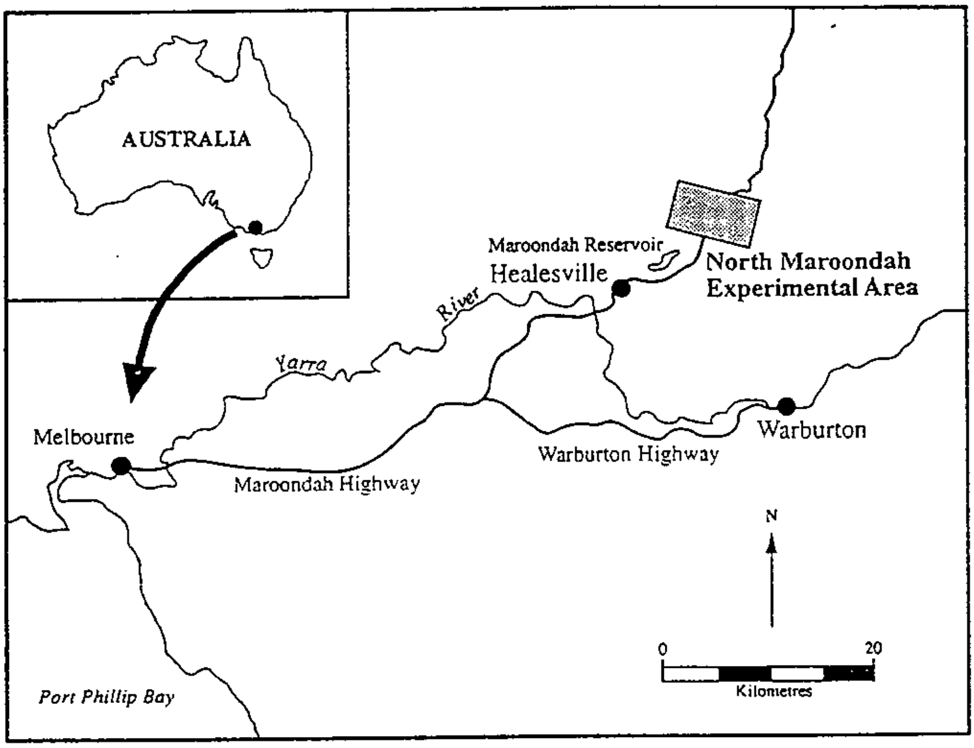

Figure 1.2 Location of the North Maroondah Experimental Area

Use of the more commonly employed micrometeorological techniques to determine evaporative flux is not possible within our study environment because of the need for a large uninterrupted fetch (Oke 1987). Therefore, evaporation from the forest floor will be determined in this study by using microlysimeter and evaporation dome techniques. The accuracy of these techniques is not known, so a further aim of this study is:

4. to determine the accuracy of evaporation measurements taken by microlysimeters and the evaporation dome.

This was done in a separate field experiment involving the intercomparison of evaporation measurements taken simultaneously by the Bowen ratio, eddy correlation, evaporation dome and microlysimeter methods in an open field.

2. MATERIALS AND METHODS

2.1 Microlysimeter construction and use

Evaporation of water from the soil is an important component of the water balance. One technique for estimating evaporation from the soil is lysimetry. In most lysimetric methods a body of soil is isolated from the surrounding soil and weighed either continuously or periodically to determine water loss (Boast and Robertson 1982). Large weighing lysimeters are expensive to construct and, because of prolonged isolation, difficulty may be experienced in trying to match the soil water conditions of the lysimeter with those of the surrounding soil.

The microlysimeter approach overcomes these problems. Microlysimeters are inexpensive to construct and can be filled with undisturbed soil and used for a short enough time that the changed hydrological boundary conditions at the bottom of the lysimeter do not appreciably affect the latent heat flux from the soil (Boast and Robertson 1982).

A number of different applications of the microlysimeter method have been reported in recent studies. Microlysimeters have been most often used to determine evaporation from beneath crop canopies (Allen 1990, Walker 1984, Todd *et al.* 1991, Leuning *et al.* 1994) and from bare soil (Paruelo *et al.* 1991, Boast and Robertson 1982, Daamen *et al.* 1993). Microlysimeters have also been used to measure grassland evaporation (Oke 1979, Tapper 1988), dewfall (Sudmeyer *et al.* 1994), and evaporation from the forest floor (Kelliher *et al.* 1992, Lafleur and Schreader 1994, Kostner *et al.* 1992). Ham *et al.* (1990) and Plauborg (1995) used microlysimeters to test the accuracy of other methods for determining evaporation while Lascano and van Bavel (1986), Klocke *et al.* (1990), and Evett *et al.* (1994) used microlysimeters to test, improve and validate models for predicting evaporation.

Microlysimeters have been found to be accurate and inexpensive to construct but the method is time consuming and labour intensive. Recently, time domain reflectometry (TDR) probes have been used within microlysimeters (Baker and Spaans 1994), allowing continuous unattended measurements of evaporation and rainfall to be made. While this technique has been found to be accurate, the greater expense involved with using TDR systems may limit its use in many investigations.

The microlysimeters used in this investigation were made from a 140 mm length of PVC pipe with an internal diameter of 85 mm. PVC was used in preference to metal tubing because it has a lower thermal conductivity. The PVC tubing was 2.5 mm thick and was closed at one end with a PVC cap. Each microlysimeter had its own sleeve, also constructed of PVC pipe but of a slightly larger diameter and length. At each site, the sleeves, each with a PVC cap, were installed in the soil so that they were flush with the surface.

Each microlysimeter was filled with a relatively undisturbed core of soil by pushing a PVC pipe, of the same diameter, 140 mm into the soil. The pipe was then dug out, and the core of soil was pushed into the microlysimeter. After filling each of the microlysimeters they were left to settle for a few hours prior to use.

After a given time interval (usually two hours), each microlysimeter was removed from its sleeve and weighed on scales which could be read to 0.01g. The difference in the weight of the microlysimeters was calculated for each time interval and used in the following equation, with the derived latent heat of vaporisation value, to determine the latent heat flux.

$$Q_E = L_v . E$$

Where:-

Q_E is the latent heat flux (W m^{-2})
L_v is the latent heat of vaporisation (J kg^{-1}) at a given environmental temperature
E is the change in weight (kg m^{-2} sec^{-1})

Studies by Boast and Robertson (1982), Shawcroft and Gardner (1983) and Daamen *et al.* (1993) considered the possible causes of error involved with the microlysimeter method. The main sources of error are, the termination of root extraction of water from the soil core once it is isolated, the conduction of heat through the microlysimeter casing, disturbance of soil during the extraction process and the cessation of drainage which results from capping the base of the microlysimeter (Daamen *et al.* 1993). The last source of error mentioned is only a problem if the soil cores are used for more than two days (Boast and Robertson 1982). From the investigations of Boast and Robertson (1982) it is estimated that the error associated with microlysimeters which are used for one or two days is less than 10%.

2.2 Evaporation dome construction and use

The evaporation dome used in this study is a simple piece of equipment for determining evaporation that can be easily transported and deployed by one person. Our device was constructed by Dr Jeff Turner of CSIRO Division of Water Resources in Perth using the basic design proposed by Stannard (1988). This is the second such dome constructed by CSIRO, the first being used for making measurements of evaporation from salt lakes (CSIRO DWR 1994). The device is analagous to a diffusion porometer which is used to measure vapour flux from leaf surfaces. As with the diffusion porometer, the evaporation dome is a short-term transient measurement method that is very sensitive to conditions at the evaporating surface. The construction and operational details for the evaporation dome are detailed below.

The device is based around a transparent plexiglass dome 4.5 mm thick and 1120 mm wide. The depth from the base to the apex of the dome is 350 mm. The hemispherical shape of the plexiglass dome minimises the occurrence of dead air spaces (Stannard 1988). A supporting frame of aluminium tubing is fitted to a horizontal flange around the perimeter of the dome, and welded to this frame are two aluminium brackets. These brackets, which are fixed on opposite sides of the supporting frame, allow the dome to be easily transported by one person with a modified hand trolley. The hand trolley has also been fitted with three plywood boxes which are used to carry the batteries, logger and a portable computer. A 20 mm square strip of foam rubber is attached to the underside of the horizontal flange to create a seal between the dome and the soil surface.

Mounted inside the dome are two small electric motors fitted with 25 mm model aircraft propellers which enable the air within the dome to be circulated. The fans are positioned to allow optimal mixing of the air and are connected to a control which enables the user to select one of four fan speeds. The fan speed which best estimates windspeed at the height of the dome is selected. The lowest fan speed is suggested for optimal air mixing.

A humidity and temperature probe (Vaisala HMP35a) is mounted on the wall of the chamber and protrudes into the chamber by 115 mm. This probe is connected to a Datataker 50 Solid State logger and the entire system, including the fans, is run off a 12 volt battery. A portable computer is connected to the logger by an RS232 cable and is used to run a program that captures humidity and temperature measurements every second and saves the data to a file on the hard disk.

To operate the evaporation dome the data capture program and fans are started while the dome itself is kept off the ground. The dome is then lowered to the ground and the time at which the dome makes contact with the soil surface is recorded. Thereafter, measurements of temperature and humidity within the dome are made each second for about one minute.

Processing of the field data to obtain an evaporative flux involves several steps. The first step is to determine the saturation vapour pressure, e_s, in Pa at the temperature within the dome using the following equation (CSIRO DWR 1994) :-

$$e_s = 6.11213 f(P) \exp\left(\frac{17.5043\, t}{241.2 + t}\right)$$

Where:- t is temperature in °C

$f(P)$ is assumed to be a constant value (100.4718), related to atmospheric pressure

From the saturation vapour pressure, the vapour density, ρ_v, of water in g m^{-3} is calculated using the following equation:-

$$\rho_v = \left(\frac{0.622e}{R_d T}\right)1000$$

Where:- R_d is the gas constant (287.04 J kg^{-1} K^{-1})

T is the temperature in K

e is the partial pressure of water vapour in Pa, calculated using relative humidity (U) measurements and the following equation:-

$$e = \frac{U e_s}{100}$$

A plot of vapour density versus time is created for each data set and the least squares method is used to determine the gradient of the rate of vapour density increase within the first five to ten seconds after the emplacement of the dome upon the soil surface. Within the first five to ten seconds the gradient is relatively constant and is at its steepest as demonstrated by Figure 2.1.

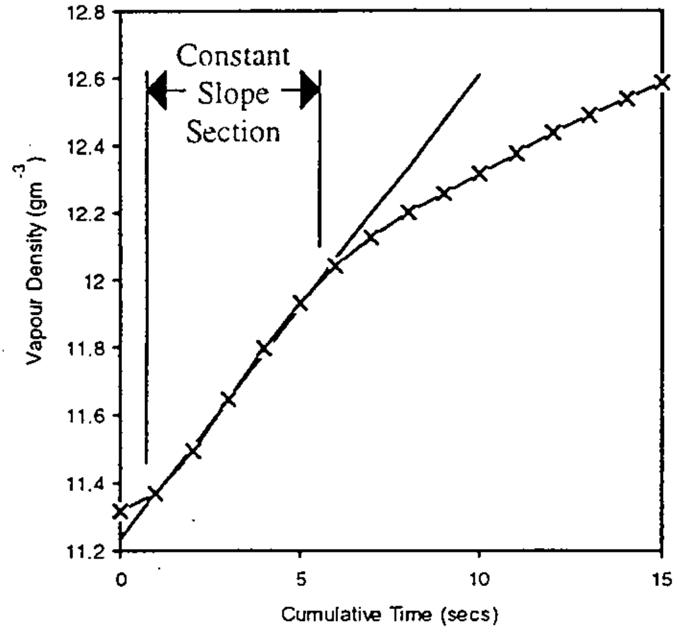

Figure 2.1 Typical plot of vapour density versus time and the constant slope section.

The gradient of the constant slope section of the vapour density time series is then used in the following equation to determine the weight of water evaporated in kg m^{-2} sec^{-1} (E):-

$$E = \frac{\left(\frac{MCV}{A}\right)}{1000}$$

Where:-

M is the gradient of the vapour density time series
C is the calibration factor of the dome (1.298) (See below)
V is the volume of the dome (0.1912 m^3)
A is the surface area covered by the dome (0. 9676 m^2)

This rate of water loss can then be converted to latent heat flux (Q_E) by multiplying by the latent heat of vaporisation (J kg^{-1}), assumed here to be constant at 2470000 J kg^{-1}.

Calibration of the evaporation dome was necessary because the internal surfaces of the dome adsorb water vapour, thereby decreasing the instruments response to the actual flux of water leaving the evaporating surface. The evaporation dome was calibrated on August 7 in the CRCCH soil physics laboratory at Monash University. Calibration was achieved by measuring and logging the weight loss of a beaker of water enclosed within the dome while concurrently measuring and logging the response of the humidity probe. Water vapour was generated at a constant rate by regulating the heat supply to the beaker of water. Once the water vapour was being generated at the desired rate, the fans and logging program for the evaporation dome were started and the dome was lowered to the bench where it covered the beaker which was positioned on a top loading balance. The start time of the logging program was then noted and every five seconds the weight loss from the beaker of water was manually recorded. After two minutes the recording of data was completed and the dome was lifted from the bench. This procedure was repeated at three different evaporation rates and replicated three times at each rate.

For each calibration measurement, the cumulative weight loss of water in the beaker and vapour accumulated by the chamber, as measured by the humidity probe, was plotted against time. The change in vapour density within the dome showed a linear trend and consequently a linear regression was used to calculate the constant slope of vapour density against time in g m^{-3} s^{-1}. Similarly, for each calibration measurement the weight loss of water from the beaker was plotted against time and the slope of this regression was used to calculate the mass of water released into the dome in g m^{-3} s^{-1}. The calibration factor was then determined from the slope of a plot of water vapour production rate as a function of water vapour accumulation rate as shown in Figure 2.2.

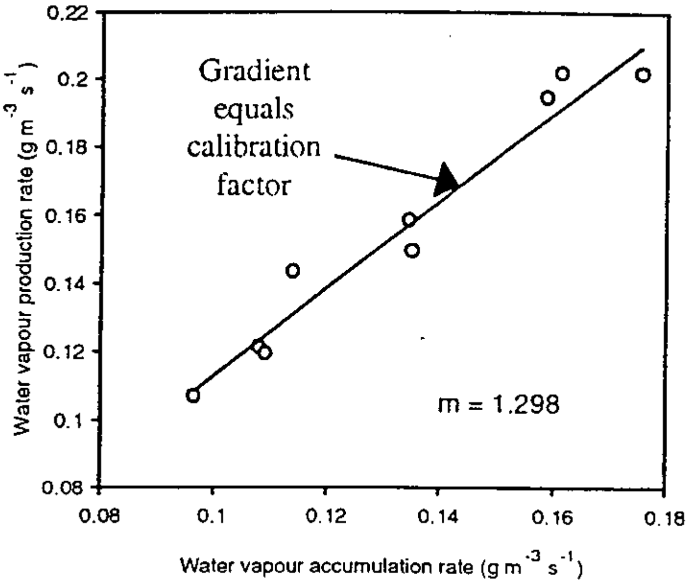

Figure 2.2 Plot of water vapour production rate versus water vapour accumulation rate for evaporation dome calibration.

2.3 Micrometeorological techniques

The Bowen ratio and eddy correlation techniques, which are described below, were used to test the validity of evaporation measurements taken with microlysimeters and the evaporation dome in an open field. This test was necessary to determine whether the microlysimeter and the evaporation dome techniques could be used to take reliable measurements of evaporation from the soil and litter beneath mountain ash forest.

2.3.1 Bowen ratio method

The Bowen ratio method for estimating convective fluxes, partitions available energy between the sensible and latent heat fluxes by considering their ratio (β) which is given by the following equation :-

$$\beta = \frac{Q_H}{Q_E}$$

The Bowen ratio method assumes that there are no marked shifts in radiation or windfields during the measurement period and that there is no vertical divergence or convergence of fluxes with height (Oke 1987). It is for these reasons that the Bowen ratio technique is problematic to apply within the forest environment. To determine the values of Q_H and Q_E all that is required are measurements of net all wave radiation (Q^*), soil heat flux (Q_G) and temperature and vapour density differences over the same height interval (Oke 1987).

The Bowen ratio system used in this investigation (Campbell Scientific) measured temperature and vapour density every second and averaged over 20 minute periods. Using temperature and vapour density differences, β was calculated using the following equation:-

$$\beta = \frac{C_a \Delta \overline{T}}{L_v \Delta \overline{\rho}_v}$$

Where:-

C_a is the heat capacity of air

$\Delta \overline{T}$ is the mean difference in temperature over the given height interval for a set period of time

L_v is the latent heat of vaporisation

$\Delta \overline{\rho}_v$ is the mean difference in vapour density over the given height interval for a set period of time

Sensible heat flux (Q_H) and latent heat flux (Q_E) were then calculated from the following equations:-

$$Q_H = \frac{\beta(Q^* - Q_G)}{(1+\beta)}$$

and

$$Q_E = \frac{(Q^* - Q_G)}{(1+\beta)}$$

When functioning correctly, the Bowen ratio method has been found to be accurate to within 10 % of the true value (Sinclair *et al.* 1975). For further details on the Bowen ratio method refer to Oke (1987, p. 382)

2.3.2 Eddy correlation method

The eddy correlation method allows direct measurement of latent and sensible heat fluxes by the correlation of fluctuations of vertical wind speed with fluctuations of vapour density and temperature respectively (Swinbank 1951). As a result of turbulent processes in the lower atmosphere, the properties of air (momentum, heat, moisture, CO_2, dust) are transferred vertically by eddies. Therefore, these properties show short-period fluctuations about their longer-term mean value (Oke 1987). The short-period fluctuation can be either a negative or positive quantity depending upon whether the quantity is above or below the mean.

By determining short period fluctuations in vertical wind velocity and vapour density, latent heat flux (Q_E) is computed as:-

$$Q_E = L_v \overline{w'\rho'_v}$$

Where:- L_v is the latent heat of vaporisation

w' is the instantaneous deviation from the mean vertical velocity

ρ' is the instantaneous deviation from the mean vapour density

(The overbar denotes the time averaged product)

To calculate sensible heat flux (Q_H) it is necessary to determine short-period fluctuations in vertical wind velocity and temperature and to use these values in the following equation:-

$$Q_H = C_a \overline{w'T'}$$

Where:- C_a is the heat capacity of air

w' is the instantaneous deviation from the mean vertical velocity

T' is the instantaneous deviation from the mean temperature

(The overbar denotes the time averaged product)

To obtain the fluxes given by the above equations it is necessary to use instruments that can rapidly sense virtually every variation in the vertical wind velocity, vapour density and temperature. The eddy correlation system needs to be able to process and record very large quantities of data and the instruments used need to be able to operate fast enough to sense the properties of the smallest eddies capable of contributing to the transport of atmospheric properties (Oke 1987). The eddy correlation system used in this investigation (Campbell Scientific) sensed fluctuations in vertical velocity using an acoustic anemometer, and sensed fluctuations in vapour pressure with an infrared hygrometer.

The eddy correlation method has the advantage of measuring the fluxes directly. If either Q_H or Q_E is determined it is fairly easy to determine the other convective flux. With additional measurements of net radiation (Q^*) and soil heat flux (Q_G) the other flux can be solved as a residual of the energy balance equation ($Q^* = Q_H + Q_E + Q_G$) (Oke 1987). For further details regarding the eddy correlation technique refer to Oke (1987 p. 375).

3. VALIDATION OF EVAPORATION MEASUREMENT TECHNIQUES

3.1 Site description

The site chosen for the comparison of techniques was a 5 ha experimental field at the Charles Sturt University Wagga Wagga campus NSW (35°10'S and 147°18'E). This site provided ideal conditions to compare techniques because the field was in fallow and there was a large fetch which is necessary for the correct functioning of the micrometeorological techniques. The experimental field was also equipped with two weighing lysimeters but unfortunately they failed to produce meaningful data during the experiment. Measurements were taken on four consecutive days from the 5th June to the 8th June. At this time the soil at the site was reasonably moist (~14.5 % of dry weight) due to light rainfall before and during the investigation period.

3.2 Sampling

Ten microlysimeters, as described previously, were installed at the commencement of measurements and after two days, ten fresh microlysimeters were installed. Microlysimeters were replaced after two days on the recommendations of Boast and Robertson (1982) and Daamen *et al.* (1993), who have determined that replacement is necessary to minimise the error produced by the conduction of heat through the microlysimeter casing and by the boundary to water flow that is produced by the base and walls of the microlysimeter. The microlysimeters were weighed once every hour during daylight and once every two to three hours during night time runs.

Measurements with the evaporation dome were taken at random locations in the central area of the field. During the day three consecutive readings were taken every half hour, while early in the night this changed to three consecutive readings every hour. When working through the middle of the night sampling was reduced further to three consecutive readings every three hours. Field data were saved in files on the portable computer and were later processed to derive Q_E values.

Equipment location in the experimental field at Wagga Wagga is shown in Figure 3.1. The eddy correlation and Bowen ratio equipment was located centrally in the field in areas unaffected by upwind obstructions. Both systems took readings every second and averaged over twenty minute time intervals, and both were equipped with net radiometer and soil heat flux plates. Q_E was measured directly using the eddy correlation method.

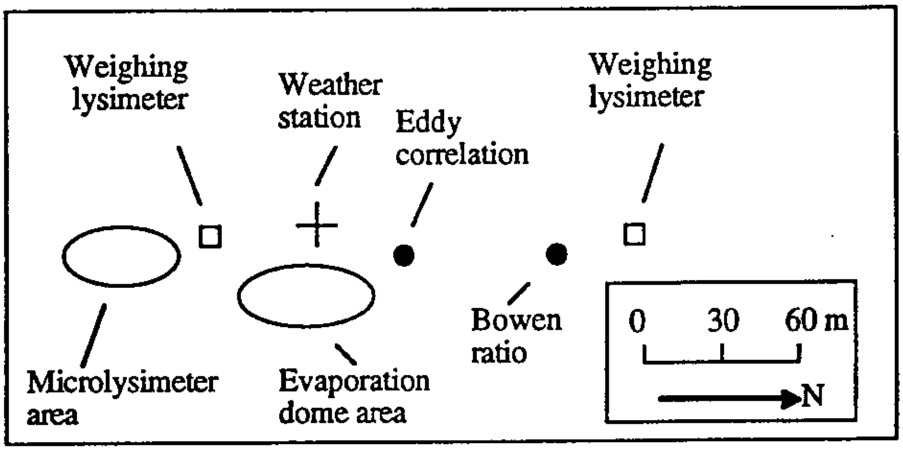

Figure 3.1 Location of the different measurement techniques in the 5 ha experimental field at Wagga Wagga.

3.3 Technique Comparison

Figures 3.2, 3.4, 3.6 and 3.8 compare Q_E estimates obtained with the eddy correlation, microlysimeter, Bowen ratio and evaporation dome techniques over the four day experimental period. The values obtained for the microlysimeters are at least hourly averages. To enable comparison, the estimates obtained using the other methods were averaged over the same time interval as the microlysimeters.

Figures 3.2, 3.4, 3.6 and 3.8 each have a corresponding table (Tables 3.1, 3.2, 3.3 and 3.4, respectively). Each table displays the gradient of the line of best fit (m) for the data points in a plot of the measurements obtained by one technique against those obtained by another technique. The gradient of this line determines the degree of agreement between the two measurement techniques in question. The correlation coefficient (r^2) for each relationship is also shown. The r^2 value is an indication of the amount of scatter of data points in the plot. Strong agreement between two measurement techniques can be assumed if m and r^2 are both close to one.

3.3.1 June 5 comparison

On June 5, Q_E measurements from the four different types of equipment showed similar trends (Figure 3.2) and modest agreement (Table 3.1). Initial readings from the micrometeorological methods were low compared to the evaporation dome and microlysimeter methods. After the first few readings Q^* fell sharply and the measurements from all instruments did not vary by more than 35 W m^{-2}. The night time Q_E

values from the micrometeorological methods were very small, but those of the evaporation dome and microlysimeter method remained relatively high, which is unusual considering the strongly negative $Q*$.

Values of m calculated for the scatter plots of microlysimeter and evaporation dome measurements, were 1.13 and 0.83 (Table 3.1). This indicates strong agreement between these methods. The agreement between these two methods and the micrometeorological techniques was not so strong (m = 0.4 to 0.55), but r^2 values between 0.88 and 0.97 indicate that the four different methods displayed similar patterns but different rates of evaporation.

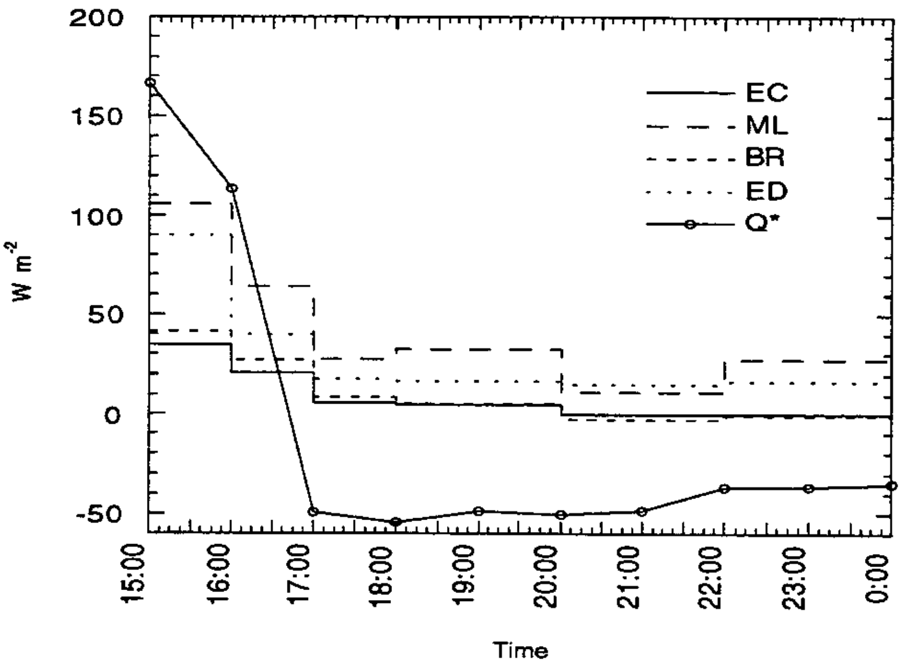

Figure 3.2 Comparison of latent heat flux at Wagga Wagga on June 5, 1995 as measured by eddy correlation (EC), microlysimeters (ML), Bowen ratio (BR) and the evaporation dome (ED). Average $Q*$ for each time period is also shown.

	Eddy correlation	Bowen ratio	Micro-lysimeter	Evaporation dome
Eddy correlation Vs	▨	m = 0.79 r^2 = 0.99	m = 0.40 r^2 = 0.97	m = 0.45 r^2 = 0.93
Bowen ratio Vs	m = 1.25 r^2 = 0.99	▨	m = 0.50 r^2 = 0.95	m = 0.55 r^2 = 0.88
Microlysimeter Vs	m = 2.44 r^2 = 0.97	m = 1.92 r^2 = 0.95	▨	m = 1.13 r^2 = 0.94
Evaporation dome Vs	m = 2.05 r^2 = 0.93	m = 1.58 r^2 = 0.88	m = 0.83 r^2 = 0.94	▨

Table 3.1 Gradient of the line of best fit (m) and correlation coefficient (r^2) for June 5 evaporation measurements obtained using four different methods.

From the June 5 data it is not possible to determine if techniques are underestimating or overestimating Q_E because high Q^* and windspeed (Figure 3.3) during the day, would be expected to produce high Q_E values, while low windspeed and strongly negative Q^* at night would be expected to produce low or even negative Q_E. In addition, equipment could still have been settling in at this early stage in the comparison.

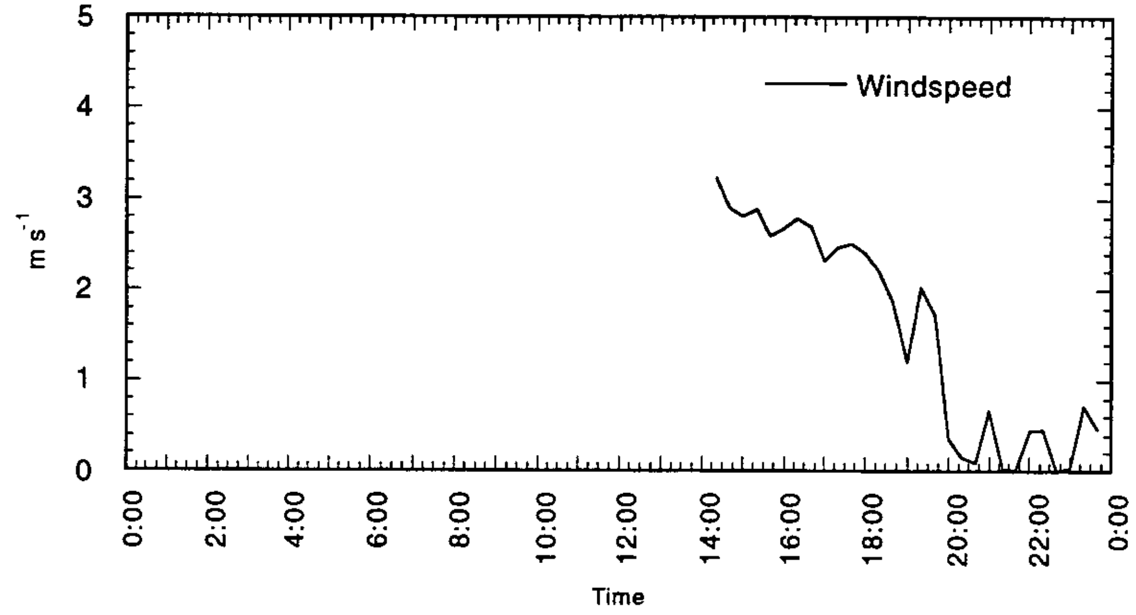

Figure 3.3 Windspeed on June 5.

3.3.2 June 6 comparison

As can be seen from Figure 3.4, measurements on June 6 were interrupted by rain and equipment failure. Despite this, enough measurements were made to compare results from the different measurement methods.

On June 6, with relatively high Q^* and windspeed (Figure 3.5) and light rain, measured Q_E values were quite high. Once again a general trend was evident through the day but some of the derived Q_E values varied by more than 50 W m^{-2}. The agreement between the microlysimeter and evaporation dome measurements was not as strong as it was on June 5. Measurements from the microlysimeters fluctuated more, possibly as a result of the influence of the earlier rainfall. Table 3.2 shows that correlation between the evaporation dome and the eddy correlation system was very strong ($r^2 = 0.99$) but the eddy correlation measurements were still considerably lower than those of the evaporation dome (m=1.49 or 0.67).

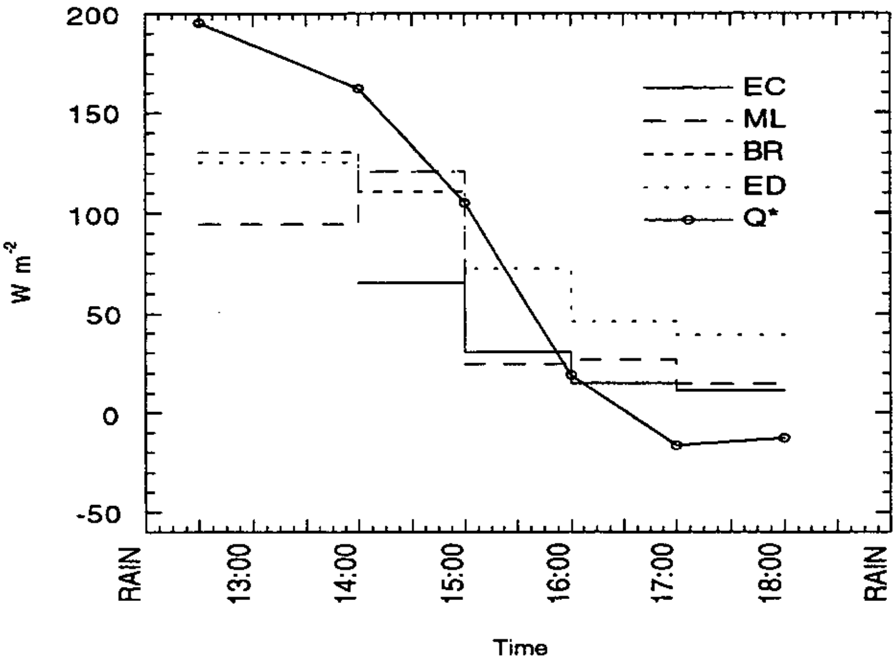

Figure 3.4 Comparison of latent heat flux at Wagga Wagga on June 6, 1995 as measured by eddy correlation (EC), microlysimeters (ML), Bowen ratio (BR) and the evaporation dome (ED). Average Q^* for each time period is also shown.

Early in the afternoon the Q_E measurements from the Bowen ratio system were very similar to those from the evaporation dome. Unfortunately, the Bowen ratio system was out of service for the remainder of the day. Measurements on June 6 were interrupted by too much rain and equipment failure to make any further comparison of results.

	Eddy correlation	Bowen ratio	Micro-lysimeter	Evaporation dome
Eddy correlation Vs	▨	?	m = 0.47 r^2 = 0.90	m = 0.67 r^2 = 0.99
Bowen ratio Vs	?	▨	?	?
Microlysimeter Vs	m = 1.92 r^2 = 0.90	?	▨	m = 1.11 r^2 = 0.88
Evaporation dome Vs	m = 1.49 r^2 = 0.99	?	m = 0.79 r^2 = 0.88	▨

Table 3.2 Gradient of the line of best fit (m) and correlation coefficient (r^2) for June 6 evaporation measurements obtained using four different methods.

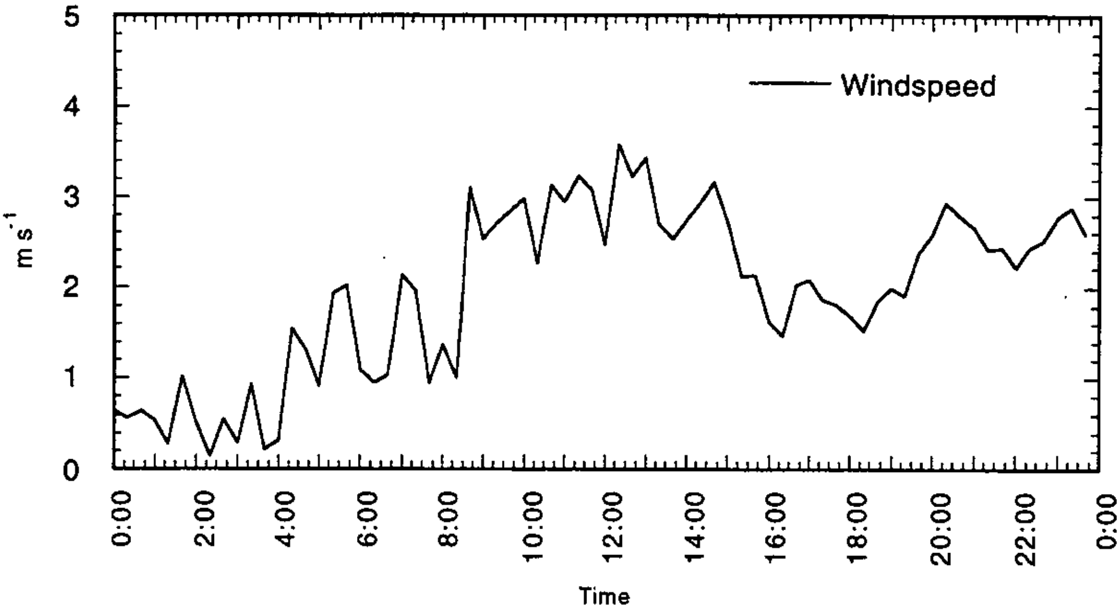

Figure 3.5 Windspeed on June 6.

3.3.3 June 7 comparison

On June 7 the rain stopped and this allowed 12.5 hours of continuous Q_E measurements to be made by all four methods. Relatively high Q^* (Figure 3.6) and windspeed (Figure 3.7) were experienced on June 7 and as a result evaporation was greater than on the previous two days.

Once again, good agreement was observed between the microlysimeter and evaporation dome measurements (m = 0.87 and 0.94, r^2 = 0.82). These two methods showed similar trends throughout the day (Figure 3.6) with the average difference between the two measurements being only 13 W m^{-2}.

The Bowen ratio measurements for June 7 showed good agreement with the microlysimeter and evaporation dome measurements for all but the highest Q_E values. For most of the day Bowen ratio measurements remained within 25 W m^{-2} of those obtained with the microlysimeter and evaporation dome techniques. Table 3.3 shows that a relatively good correlation (r^2 = 0.88) was established between the Bowen ratio measurements and those of the evaporation dome. Although they correlated well, m values of 0.74 and 1.24 for these techniques reflect the fact that the Bowen ratio system consistently yielded lower estimates of Q_E.

Eddy correlation measurements were lower than those obtained from the other methods. Despite this, the eddy correlation and Bowen ratio measurements had an r^2 value of 0.97 indicating that the two methods showed similar patterns.

It is evident from the first three days of measurement, that the microlysimeters and evaporation dome consistently estimated higher Q_E values than those of the eddy correlation and Bowen ratio techniques, particularly during the middle of the day when Q^* was at its highest.

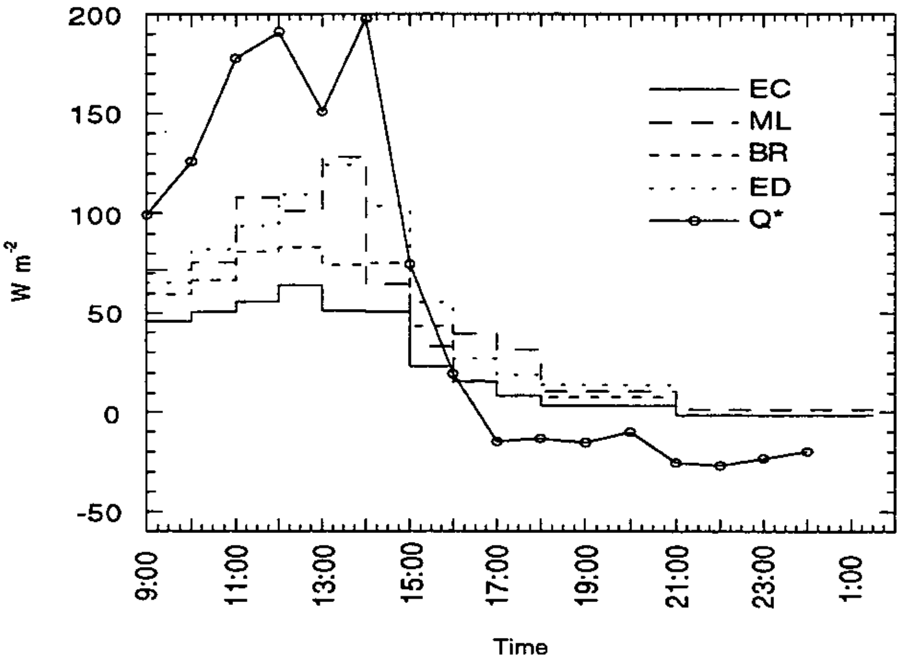

Figure 3.6 Comparison of latent heat flux at Wagga Wagga on June 7, 1995 as measured by eddy correlation (EC), microlysimeters (ML), Bowen ratio (BR) and the evaporation dome (ED). Average Q* for each time period is also shown.

	Eddy correlation	Bowen ratio	Micro-lysimeter	Evaporation dome
Eddy correlation Vs	▨	m = 0.71 $r^2 = 0.97$	m = 0.53 $r^2 = 0.83$	m = 0.52 $r^2 = 0.88$
Bowen ratio Vs	m = 1.38 $r^2 = 0.97$	▨	m = 0.72 $r^2 = 0.80$	m = 0.74 $r^2 = 0.92$
Microlysimeter Vs	m = 1.58 $r^2 = 0.83$	m = 1.11 $r^2 = 0.80$	▨	m = 0.87 $r^2 = 0.82$
Evaporation dome Vs	m = 1.70 $r^2 = 0.88$	m = 1.24 $r^2 = 0.92$	m = 0.94 $r^2 = 0.82$	▨

Table 3.3 Gradient of the line of best fit (m) and correlation coefficient (r^2) for June 6 evaporation measurements obtained using four different methods.

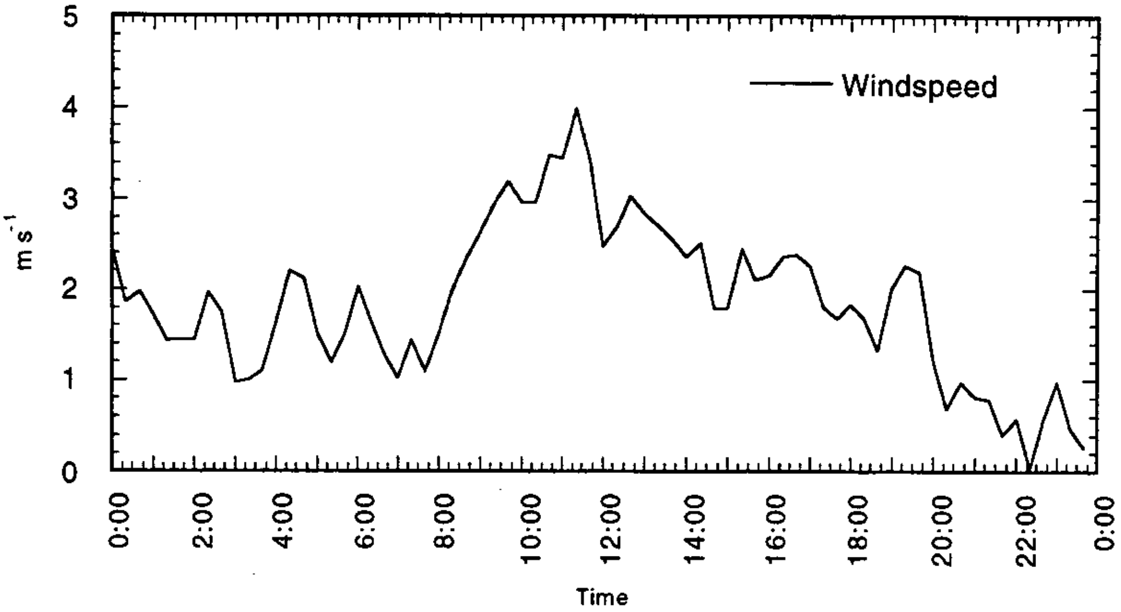

Figure 3.7 Windspeed on June 7.

Analysis of materials used in the construction of microlysimeters and the effects of these materials on microlysimeter temperatures and evaporation has been undertaken by Evett *et al.* (1995). They found that the low thermal conductivity of PVC caps restricted the transfer of heat from the bottom of the microlysimeter to the soil below, therefore causing the accumulation of heat inside the microlysimeter and, as a result, greater evaporation. Microlysimeters used in this study had PVC caps so the findings of Evett *et al.* (1995) may explain the observed increase in variation between the microlysimeters and micrometeorological techniques when Q^* is at its highest. To confirm such an explanation, soil temperatures both inside and outside the microlysimeters would need to be compared.

Dugas *et al.* (1991) compared diurnal Q_E measurements taken by four Bowen ratio systems, an eddy correlation system and a portable chamber. In the middle of the day they too observed greater estimations of Q_E from their portable chamber. Also similar to this investigation is that Q_E values measured by their portable chamber continued to increase for some time after the peak in Q^* while the micrometeorological techniques showed a distinct reduction in Q_E. Dugas *et al.* (1991) inferred the advection of dry air from an adjacent bare soil field next to the portable chamber site as the cause of the observed differences between the measurement techniques. Such an explanation is not possible in this investigation because all of the instruments were confined to one area. The effect of the speed of the fans inside the evaporation dome on the measured evaporation rate has not yet been investigated, but is likely to influence estimated Q_E values. If the fans are circulating air faster than the near surface wind, it could be expected that water vapour would be transported away from the soil surface at a faster rate, therefore causing the evaporation dome to estimate higher Q_E values. High Q_E values obtained with the evaporation dome during periods of strong Q^* could then be explained by the combination of abundant water vapour at the soil surface and faster air movement within the evaporation dome.

3.3.4 June 8 comparison

The best agreement between measurements obtained with the four different methods was obtained on June 8. On this day the Q_E values do not get as high as on previous days due to the low windspeed (Figure 3.9) and relatively low Q^*. The low Q_E values may contribute to the agreement between measurements from the four different techniques because other days have shown the least agreement between techniques when Q^* exceeded 100 W m^{-2}. Despite this fact there was excellent agreement between all four measurement techniques (Figure 3.8).

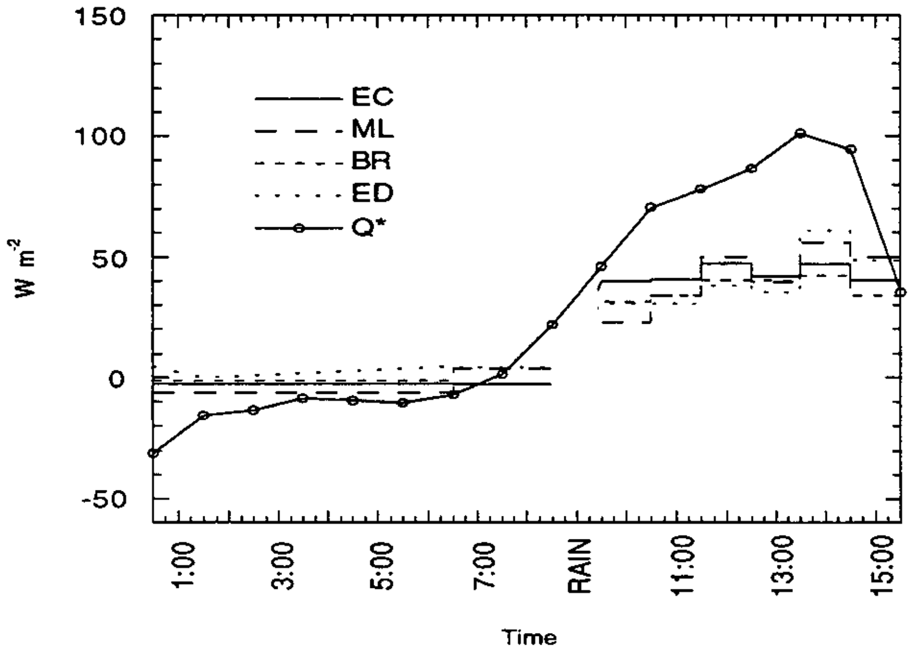

Figure 3.8 Comparison of latent heat flux at Wagga Wagga on June 8, 1995 as measured by eddy correlation (EC), microlysimeters (ML), Bowen ratio (BR) and the evaporation dome (ED). Average Q^* for each time period is also shown.

The average range between the maximum and minimum measurements from the four techniques was only 12 W m-2 with the greatest difference being less than 20 W m-2. It is surprising that the four methods maintained such good agreement because of the occurrence of rainfall early in the day. Table 3.4 confirms the good agreement between the four measurement techniques.

	Eddy correlation	Bowen ratio	Micro-lysimeter	Evaporation dome
Eddy correlation Vs	▨	m = 1.15 $r^2 = 0.99$	m = 0.85 $r^2 = 0.84$	m = 0.97 $r^2 = 0.79$
Bowen ratio Vs	m = 0.86 $r^2 = 0.99$	▨	m = 0.74 $r^2 = 0.86$	m = 0.84 $r^2 = 0.80$
Microlysimeter Vs	m = 0.99 $r^2 = 0.84$	m = 1.15 $r^2 = 0.86$	▨	m = 1.12 $r^2 = 0.90$
Evaporation dome Vs	m = 0.81 $r^2 = 0.79$	m = 0.94 $r^2 = 0.80$	m = 0.81 $r^2 = 0.90$	▨

Table 3.4 Gradient of the line of best fit (m) and correlation coefficient (r^2) for June 8 evaporation measurements obtained using four different methods.

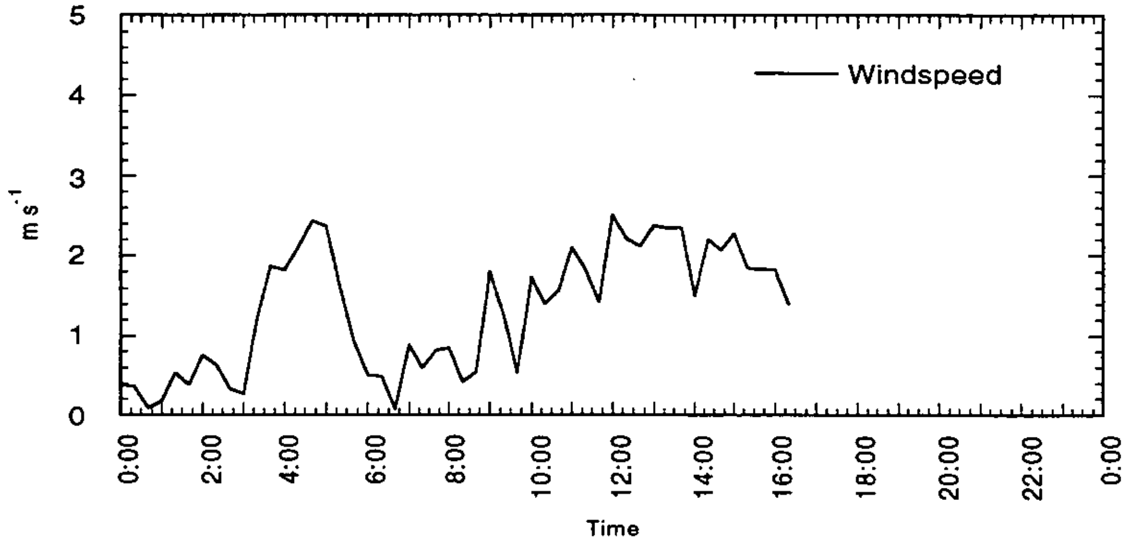

Figure 3.9 Windspeed on June 8.

3.3.5 June 5 - 8 comparison

A scatter plot of Q_E measurements taken using the eddy correlation, Bowen ratio and evaporation dome techniques against those taken with microlysimeters shows how variation between measurements increases as Q_E becomes larger (Figure 3.10). Measurements taken by the evaporation dome and microlysimeters are the most closely matched over the observation period. As observed throughout this comparison, the micrometeorological techniques showed the best agreement with the microlysimeter method when Q_E values were low.

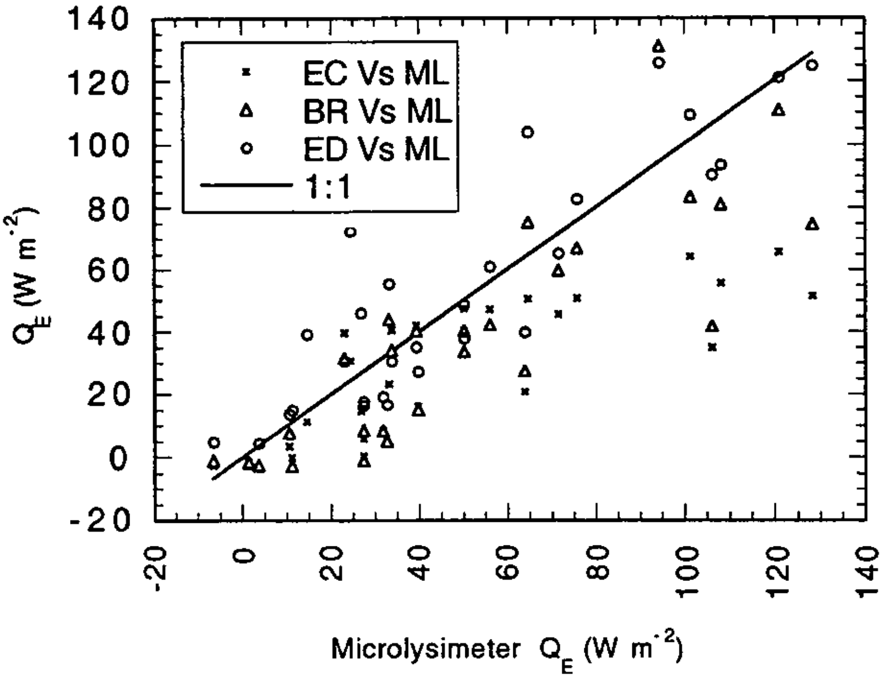

Figure 3.10 Scatter plot of Q_E measurements taken with the eddy correlation (EC) and Bowen ratio (BR) techniques and evaporation dome (ED) against those taken with microlysimeters (ML) from June 5-8.

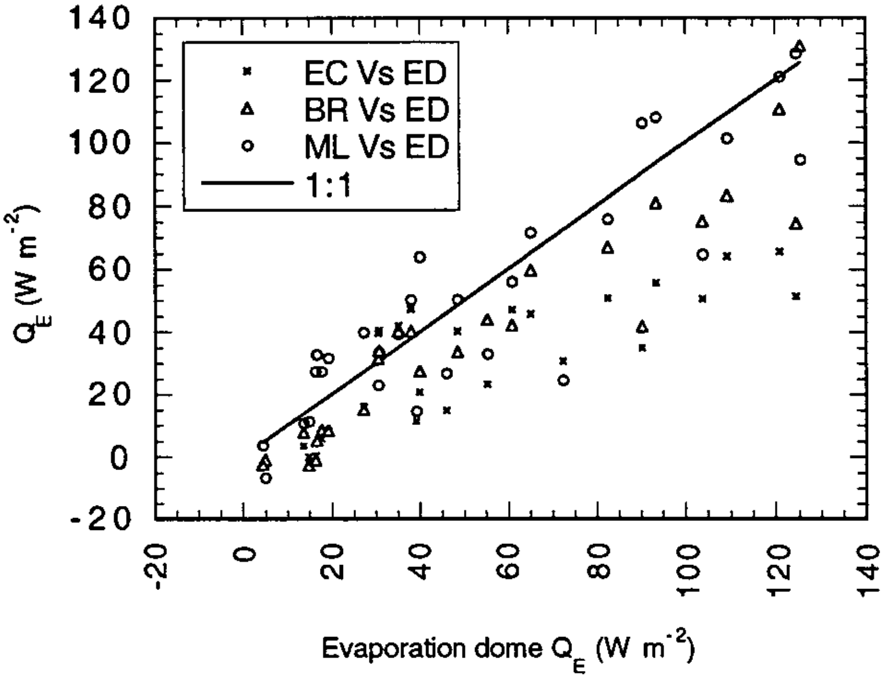

Figure 3.11 Scatter plot of Q_E measurements taken with the eddy correlation (EC) and Bowen ratio (BR) techniques and the microlysimeter (ML) method against those taken with the evaporation dome (ED) from June 5-8.

A similar pattern to that shown in Figure 3.10 arose in the scatter plot of Q_E measurements taken using the eddy correlation, Bowen ratio and microlysimeter techniques plotted against those of the evaporation dome (Figure 3.11). However, Figure 3.11 also shows that for most measurements the evaporation dome overestimated Q_E. Best agreement between the evaporation dome and other techniques occurred at low Q_E rates.

After four days of evaporation measurements the total amounts of evaporation estimated by the microlysimeter method and evaporation dome were very similar (Table 3.5). Total evaporation estimates from the two micrometeorological techniques were also very similar but were almost half that of the estimates obtained with the microlysimeters and evaporation dome. However, it must be noted that on June 6 the micrometeorological measurements were incomplete, so their totals are not accurate.

DATE	Eddy correlation	Bowen ratio	Microlysimeter	Evaporation dome
June 5	0.102 mm	0.117 mm	0.496 mm	0.355 mm
June 6	0.178 mm*	????? mm*	0.410 mm	0.589 mm
June 7	0.539 mm	0.765 mm	1.007 mm	1.052 mm
June 8	0.344 mm	0.307 mm	0.322 mm	0.412 mm
TOTAL	1.164 mm*	1.189 mm*	2.235 mm	2.408 mm

Table 3.5 Evaporation equivalent in depth of water from June 5 to June 8. *(Note: On June 6 eddy correlation and Bowen ratio measurements are incomplete)

Comparison of evaporation determined by the four different methods on individual days shows similar trends to the total estimates, except on June 8 when evaporation was similar and amongst all methods, varying by no more than 25%.

3.5 Summary

The best agreement between Q_E measurements occurred when Q^* was less than 100 W m^{-2}. On June 8 this was the case for most of the day and the maximum variation between measurements obtained by the four different methods was less than 20 W m^{-2}. Measurements from the different techniques diverged with increasing Q^* and then converged as Q^* decreased again. During the times of highest Q^* the evaporation dome and microlysimeters probably overestimated Q_E.

The fact that the best agreement between evaporation measurements occurred when Q^* was low increases the confidence with which the evaporation dome and microlysimeters can be used within the forest. This is because Q^* at the forest floor is always low due to shading produced by the canopy and understorey.

The problem of heat accumulation in the microlysimeters due to the PVC caps would not be a major concern within the forest due to the combination of low Q^* at the forest floor, low soil temperatures and insulation of the soil by leaf litter.

4. SOIL AND LITTER EVAPORATION BENEATH RE-GROWTH AND OLD GROWTH MOUNTAIN ASH FOREST

In the previous chapter, total latent heat flux (Q_E) in the Wagga Wagga experiment was contributed only by soil evaporation. Within the forest environment, transpiration from the vegetation, evaporation of intercepted water on plant canopies and evaporation from the soil and litter all contribute to Q_E. Because only soil and litter evaporation was measured in the mountain ash forest in this study, it will be referred to henceforth as Q_{Es}.

4.1 Site descriptions

The Myrtle 1 experimental catchment is dominated by old-growth mountain ash forest of 235 years of age. The trees are about 80 m high and are interspersed with mountain ash re-growth from the 1939 bushfires which reach heights of about 50 m. The dense understorey is dominated by woody species up to 15 m in height and a discontinuous ground stratum of herbs, ferns, sedges and mosses (Langford and O'Shaughnessy 1977). The leaf area index (LAI) for this site is about 3.5 (O'Sullivan pers. comm. 1995).

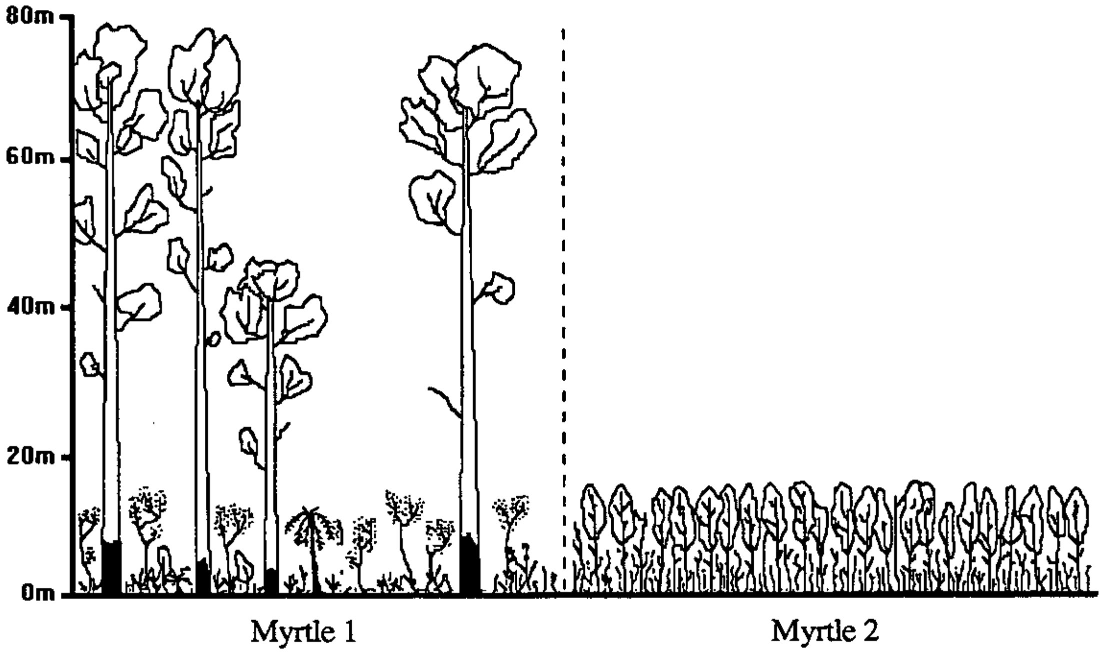

Figure 4.1 Forest structure profile at Myrtle 1 and Myrtle 2.

The Myrtle 2 experimental catchment was cleared of old-growth forest in 1984. The forest has since regenerated as a dense stand of mountain ash reaching 10-15 m in height. Understorey vegetation within this catchment is limited to a few woody species with minimal leaf area. The high density of the mountain ash re-growth at Myrtle 2 gives this experimental catchment an LAI of about 4.2 (O'Sullivan pers. comm. 1995). The structure of the forest at Myrtle 2 as compared to that at Myrtle 1 is depicted in Figure 4.1.

The root systems of the re-growth and old-growth mountain ash trees are also quite different. Ashton (1975) found that typical 10 year old mountain ash trees had a root system with a radius of around 4 m, with most roots restricted to the top 50 cm of soil. Typical mature mountain ash trees (100-300 years old) were found to have a root system with a radius of around 9 m with roots reaching depths greater that 10 m. The density and depth of the roots can have important implications for soil moisture depletion.

Similarity in the aspect, slope, area, elevation and mean annual rainfall at Myrtle 1 and Myrtle 2 (Table 4.1), makes these two sites ideal for isolating and investigating the effect of forest age on evaporation from the soil.

	MYRTLE 1	MYRTLE 2
AVERAGE ASPECT	141°	148°
AVERAGE SLOPE	20°	21°
CATCHMENT AREA	25.21 ha	30.48 ha
HIGHEST ELEVATION	815 m	795 m
LATITUDE	37°34.6'S	37°34.9'S
LONGITUDE	145°37.1'E	145.36.9'E
MEAN ANNUAL RAINFALL (1972-76)	1622 mm	1590 mm

Table 4.1 Myrtle 1 and Myrtle 2 site characteristics (Langford and O'Shaughnessy 1977)

4.2 Sampling

At Myrtle 1, twenty microlysimeters were installed at different locations in the understorey in an attempt to account for the variations in vegetation. Microlysimeters were installed beneath ferns, shrubs, and understorey trees and some were installed in unvegetated areas of forest floor. At Myrtle 2, twenty microlysimeters were installed in random locations around the central weighing point. The positioning of the microlysimeters at Myrtle 2 was not so important due to the lack of different species in the understorey vegetation and relatively uniform forest floor conditions.

Q_{Es} measurements were made during five twenty-four hour observation periods in February, March, May, July and October. Measurements with the evaporation dome and microlysimeters were weighed every two hours during the day and early part of the night. were taken after the microlysimeters were weighed. The evaporation dome was used at three fixed locations at each site in areas devoid of ground vegetation. Vegetation was kept out of the evaporation dome to enable fans to operate properly and to ensure that only evaporation from the soil and litter was being measured without any contribution of water transpired by plants.

Q^* and Q_G were monitored at Myrtle 2 during the last four measurement runs. Despite attempts to make comparable measurements at Myrtle 1, continuous equipment failure prevented this on all but the last measurement run. Solar radiation shows large variability beneath forest canopies and a large number of radiometers are needed to sample radiation with a reasonable degree of accuracy (Reifsnyder *et al.* 1971). Because only one net radiometer and soil heat flux plate were used at each site, the values derived from these instruments needs to be treated with a certain degree of caution.

During all runs, temperature measurements were made with a digital thermometer and during the March and October measurement runs, a whirling psychrometer was used to take wet and dry bulb temperatures for calculating vapour pressure. After the first measurement run, it was proposed that windspeed at the forest floor could contribute to Q_{Es}, so attempts were made to measure below canopy windspeed with a hand-held anemometer. During these attempts windspeed was below the detectable level of the anemometer, so further measurements were not made. However, during the October measurement run below canopy windspeed at both sites was stronger than previously experienced, but without any way of measuring the actual windspeed only field observations of the wind conditions could be made.

4.3 Comparison of soil and litter evaporation rates

In this section, each observation period will be examined in turn and diurnal variation in evaporation in 235 and 10 year old forest will be compared. Only the microlysimeter measurements are used in this comparison because the evaporation dome did not become available until May. The evaporation dome data are used in the next section where daily rates of evaporation determined by both techniques will be compared.

The maximum and minimum temperatures at Myrtle 1 and Myrtle 2 during the different observation periods are shown by Figure 4.2 and Figure 4.3, respectively. Soil moisture contents for the last three observation periods are shown in Figure 4.4.

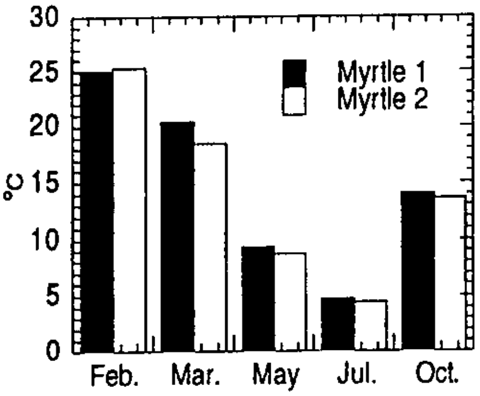

Figure 4.2 Maximum temperatures on measurement days.

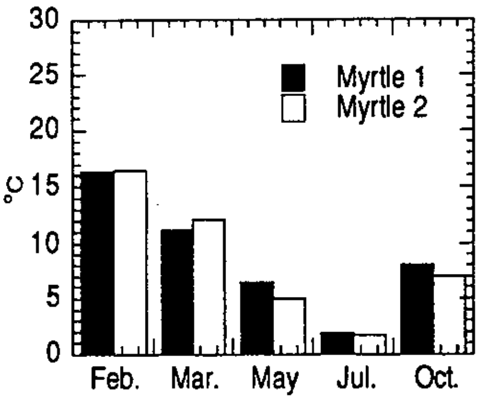

Figure 4.3 Minimum temperatures on measurement days.

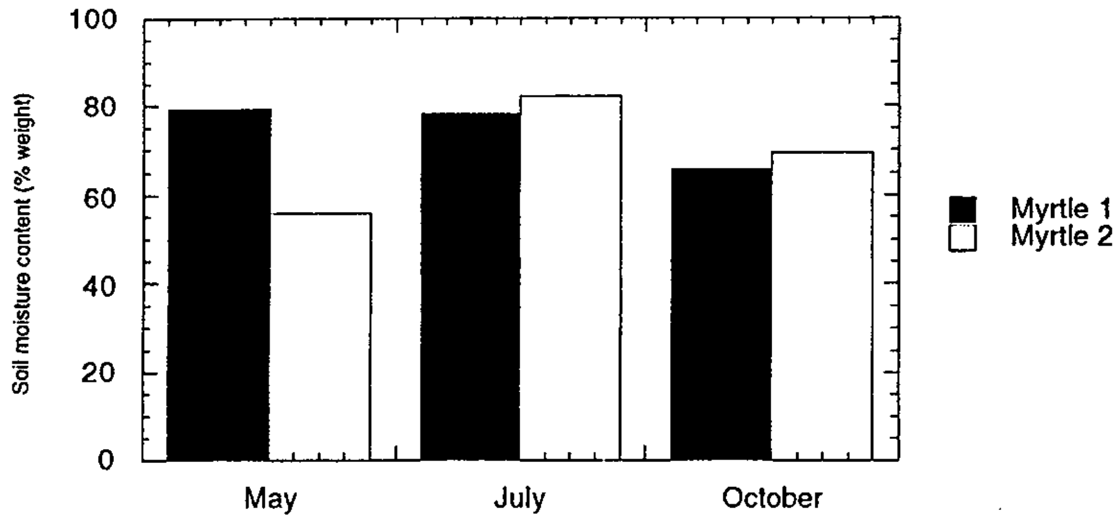

Figure 4.4 Soil moisture content on measurement days.

4.3.1 February 14-15 measurements

On February 14 and 15 fine weather conditions were experienced with temperatures in the forest rising above 25°C during the day and dropping to only 16°C during the night. Maximum and minimum temperatures at Myrtle 2 were slightly greater than those at Myrtle 1 (Figures 4.2 and 4.3). Temperatures were expected to be higher at Myrtle 1 due to the more open canopy. At Myrtle 2 it may have been possible for heat which had accumulated in the dense canopy to have been transferred downwards, therefore contributing to higher temperatures within the forest. During this measurement run the forest soil was moist but the leaf litter was quite dry due to the combination of hot days and lack of rainfall over summer. Very light but steady winds were observed at Myrtle 2, while at Myrtle 1 air movement was caused by occasional light gusts.

Late afternoon to early morning Q_{Es} values at both sites remained relatively constant (Figure 4.5). The average value between 17:30 and 10:30 at Myrtle 1 was about 10 W m^2 while at Myrtle 2 it was slightly higher at 15 W m^{-2}. Although this difference is small, it translates to a 0.12 mm difference in night time Q_{Es}. The higher values in the 10 year old forest could possibly be due to the slightly greater air movement and the distance from the active surface to the forest floor. In the 10 year old forest, heat stored in the dense forest canopy and heat released from biochemical reactions is more likely to become available at the forest floor because the canopy is only a few metres from the ground. A distance of more than 50 m often separates the floor and the canopy in 235 year old forest, therefore reducing the likelihood of energy from the canopy becoming available at the forest floor. The dense canopy of the 10 year old forest is also more likely to have reduced nocturnal longwave radiation loss from the forest.

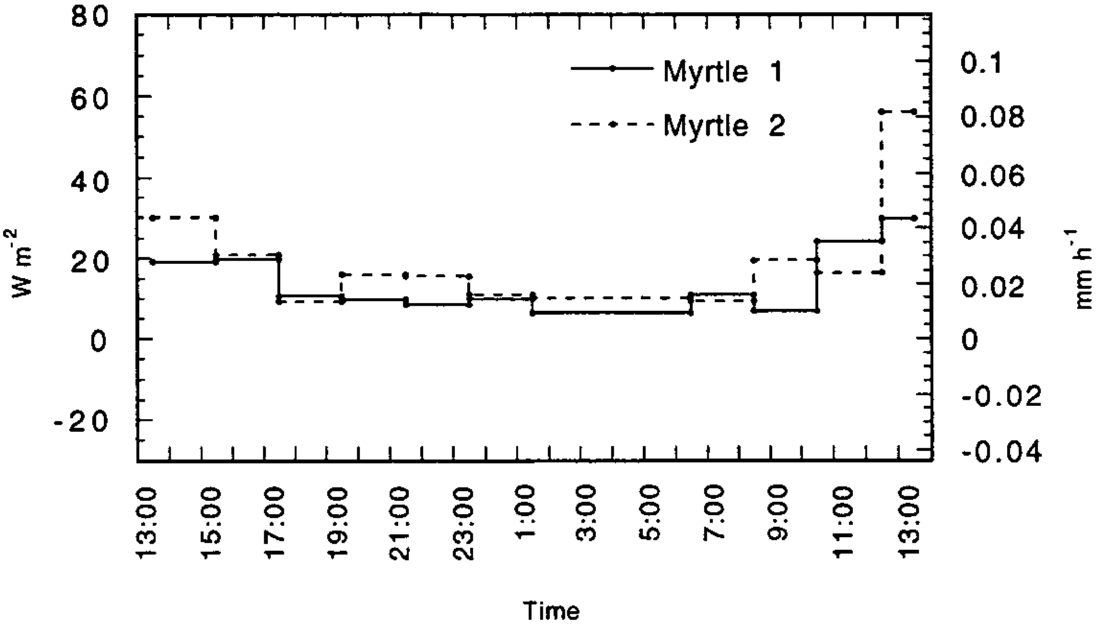

Figure 4.5 Microlysimeter estimates of Q_{Es} during indicated time intervals on February 14-15 at Myrtle 1 and Myrtle 2.

Continual nocturnal moisture loss from the surface, such as that observed in both the 10 and 235 year old forest, is not typical of most surfaces. This is because of Q^* loss during the night and the need for transfer of energy from the environment via Q_E, sensible heat flux (Q_H), and Q_G to balance this loss (Arya 1988, Oke 1987). Therefore the pattern of continual moisture loss from the soil and litter which was observed in both the re-growth and old-growth mountain ash forest is somewhat unique.

Both ages of forest showed peaks in Q_{Es} at around midday. Q_{Es} values started to increase after 10:30 when the sun began to penetrate through the canopy, and then fell back to previous levels after 17:30 when the sun began to set. As well as having a higher average Q_{Es} value from late afternoon to early morning, the 10 year old forest also showed significantly higher values in the middle of the day with a maximum flux of 55 W m^{-2} as compared to the maximum flux of 30 W m^{-2} in the 235 year old forest. The lower values in the 235 year old forest are likely to have been caused by slower and less continuous air movement at the forest floor level, and the interception of sunlight which had penetrated through the canopy and understorey trees by the dense ground stratum which is dominated by ferns. According to LAI, the interception of sunlight is less at Myrtle 1 than it is at Myrtle 2, but it must be pointed out that leaf area measurements are made at a height of about 1.5 m and therefore do not include the leaf area below this level, which at Myrtle 1 is quite substantial.

Although the amount of energy available within the forest environments was quite high and the soil reasonably moist, Q_{Es} was quite small. A possible explanation for this observation is that the soil was decoupled from the atmosphere by the dry layer of leaf litter which insulates the soil. This gives some indication that Q_{Es} at this time of year is limited by the availability of the moisture held within the soil.

4.3.2 March 11-12 measurements

The second measurement run commenced on March 11 with clear sky conditions. On this occasion Q^* and Q_G measurements were made at Myrtle 2 (Figure 4.7). Clear conditions prevailed through the night but cloud cover developed early the next morning. Temperatures for the measurement period reached a maximum of 20 °C and fell to a low of about 11°C. Maximum and minimum temperatures at Myrtle 1 were 1 to 2 °C higher than at Myrtle 2 (Figures 4.2 and 4.3). Air movement in both the re-growth and old-growth forest was very limited and was undetectable with an anemometer.

On March 11 and 12, Q_{Es} values in the 235 and 10 year old forest covered similar ranges (Figure 4.6), though the timing of maximum Q_{Es} at these sites was different. At Myrtle 2, Q_{Es} gradually increased through the afternoon while at Myrtle 1 it rapidly rose to its peak soon after midday. This observed difference could have resulted from the different canopy leaf area of these sites. The more open canopy of Myrtle 1 is more likely to have allowed the maximum amount of energy to be received by the forest floor when the sun was more directly overhead, while the higher leaf area at Myrtle 2 would have favoured the trapping and accumulation of heat as the day progressed.

Both sites showed a distinct drop in Q_{E_s} soon after sunset, followed by an increase and continuous positive values through the night. The drop in Q_{E_s} after sunset could indicate a transitional phase between energy being supplied by sunlight and energy being supplied by the downward transfer of heat from the canopy.

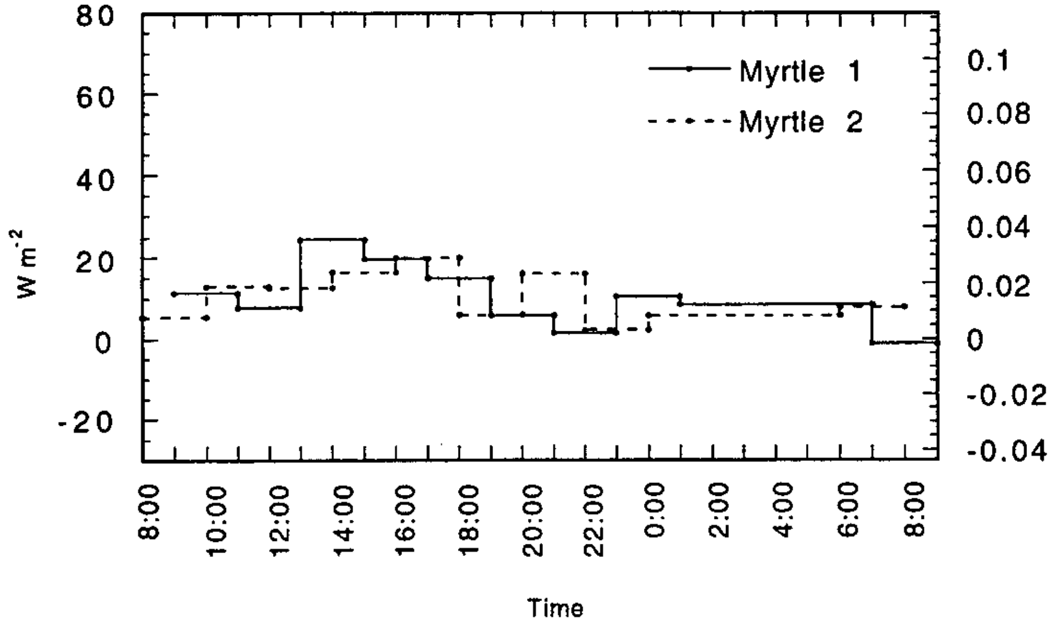

Figure 4.6 Microlysimeter estimates of Q_{E_s} at indicated times on March 11-12 at Myrtle 1 and Myrtle 2.

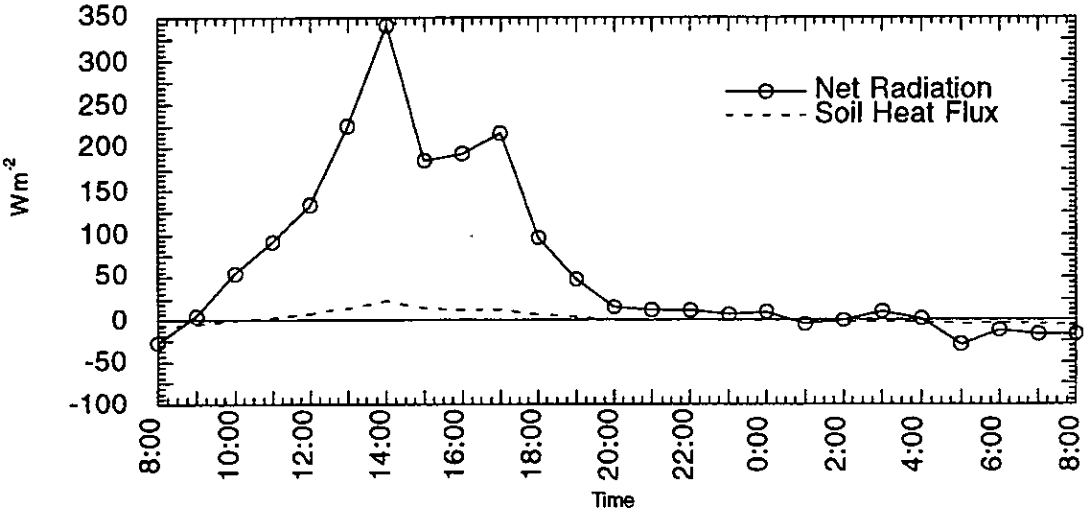

Figure 4.7 Net radiation and soil heat flux at Myrtle 2 for March 11-12.

Overall, the Q_{E_s} values for both sites show some distinct similarities. Once again it is probable that a lack of soil moisture is the limiting factor on Q_{E_s} because of the relatively high Q^* experienced during the measurement run. Values of Q_G were relatively low, ranging from a maximum of 15 W m^{-2} during the day to a minimum of -9 W m^{-2} during the night (Figure 4.7). This was most probably as a result of the low thermal conductivity of the overlying litter which could have limited the transfer of heat to and from the soil.

The diurnal variation in vapour pressure at both sites (Figure 4.8) showed similar trends. During the middle of the day, vapour pressure was at its highest because this was when the input of moisture to the atmosphere via evaporation and transpiration was at its greatest. During the night, vapour pressure gradually decreased, resulting in a stronger forest floor to atmosphere vapour gradient which may have contributed to the continuation of evaporation throughout the night.

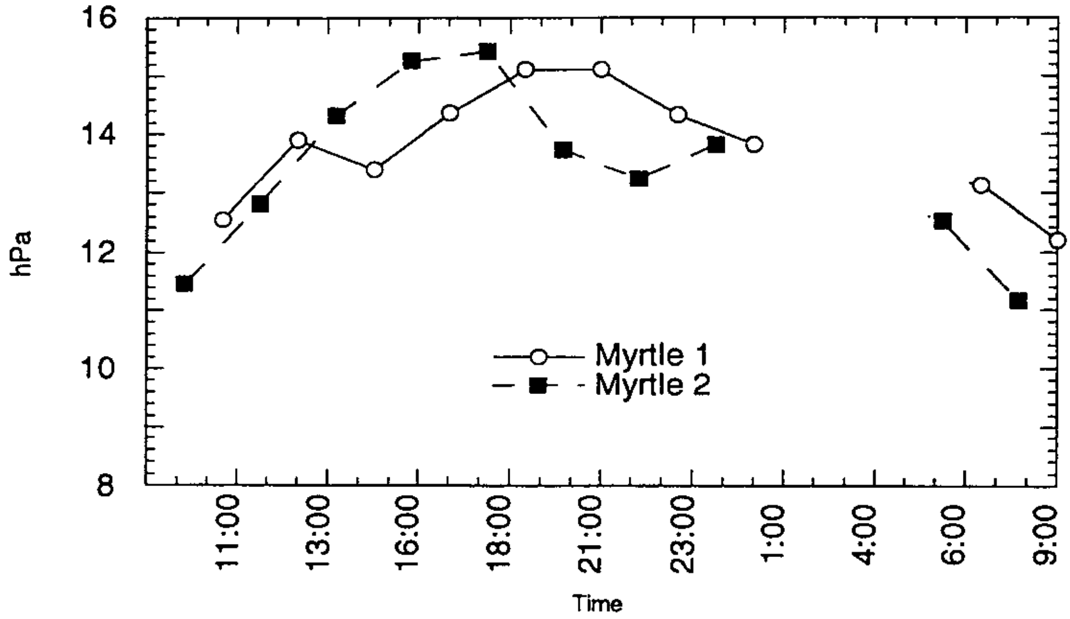

Figure 4.8 Vapour pressure during indicated time intervals on March 11-12 at Myrtle 1 and Myrtle 2.

As on the previous run, Q_{E_s} continued through the night. The nocturnal energy balance is shown in Figure 4.9. Q_{E_s}, Q^* and Q_G were measured and Q_H was determined as a residual. Being calculated as a residual, Q_H has the combined errors of the microlysimeters, net radiometer and soil heat flux plate. Estimated error for Q_{E_s} and Q^* measurements was 10 %, whereas for Q_G it was 5%. This means that the maximum error of the Q_H estimate was 25%. From Figure 4.9 it can be seen that when nocturnal Q_{E_s} values exceeded the radiant energy supply below the canopy it was balanced by a downward flux of sensible heat.

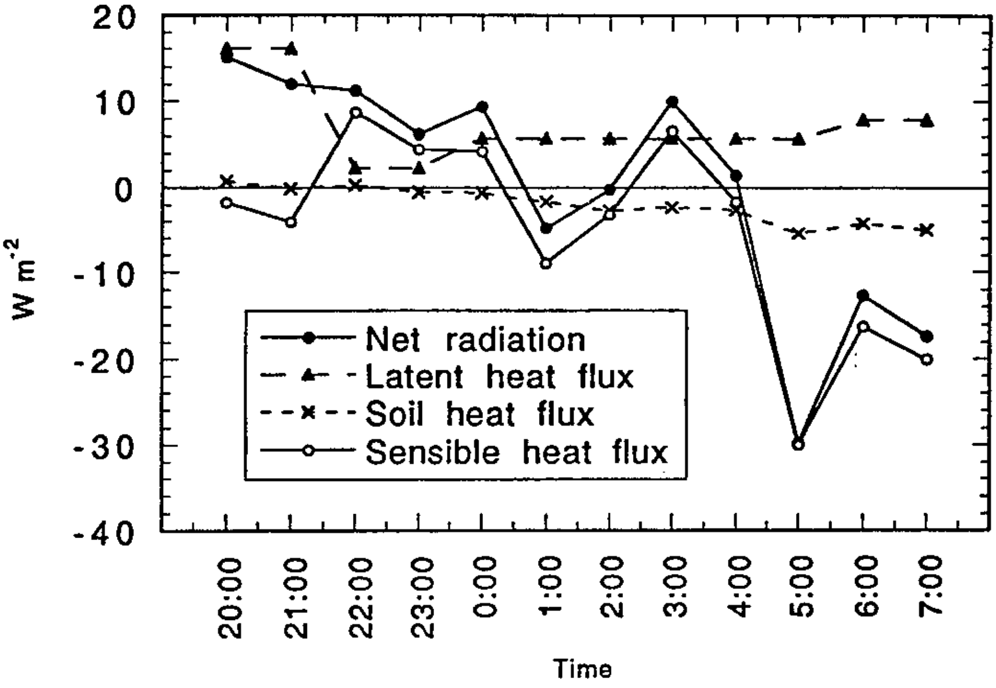

Figure 4.9 Nocturnal energy balance at Myrtle 2 for March 11-12.

Walker (1984) observed nocturnal evaporation from soil beneath crop canopies and argued that the production of sensible heat at the foliage elements and its transport to the soil surface was the cause for this. It is probable that a similar situation occurred within both the re-growth and old-growth forest with sensible heat being transferred from foliage elements to the forest floor. To confirm this assertion, measurements of Q_H within the canopy would be necessary, but as yet there are no micrometeorological techniques that can do this. It is interesting to note that Q^* at Myrtle 2 remained positive until midnight (Figure 4.9) indicating strong input of longwave radiation from the canopy to the forest floor.

4.3.3 May 23-24 measurements

At the commencement of measurements on May 23 the sky conditions were clear but cloud cover increased later in the day and into the night. Temperatures during this measurement run showed little diurnal variation ranging from 6 to 9 °C. Once again, maximum and minimum temperatures were slightly higher at Myrtle 1 (Figures 4.2 and 4.3). Measurement of the soil moisture content during this run (Figure 4.4) revealed that the soil at Myrtle 2 had only 70% of the moisture content measured at Myrtle 1. This implies that the preceeding period of Q_{E_s} and/or drainage was greater than at Myrtle 1. Windspeed during this measurement run was negligible.

During most of the May 23-24 measurement period Q_{Es} values in the re-growth and old-growth forest remained low (< 10 W m^{-2}) (Figure 4.10). As on previous runs, low Q_{Es} values were measured around sunset with negative evaporation, or dewfall, at Myrtle 2.

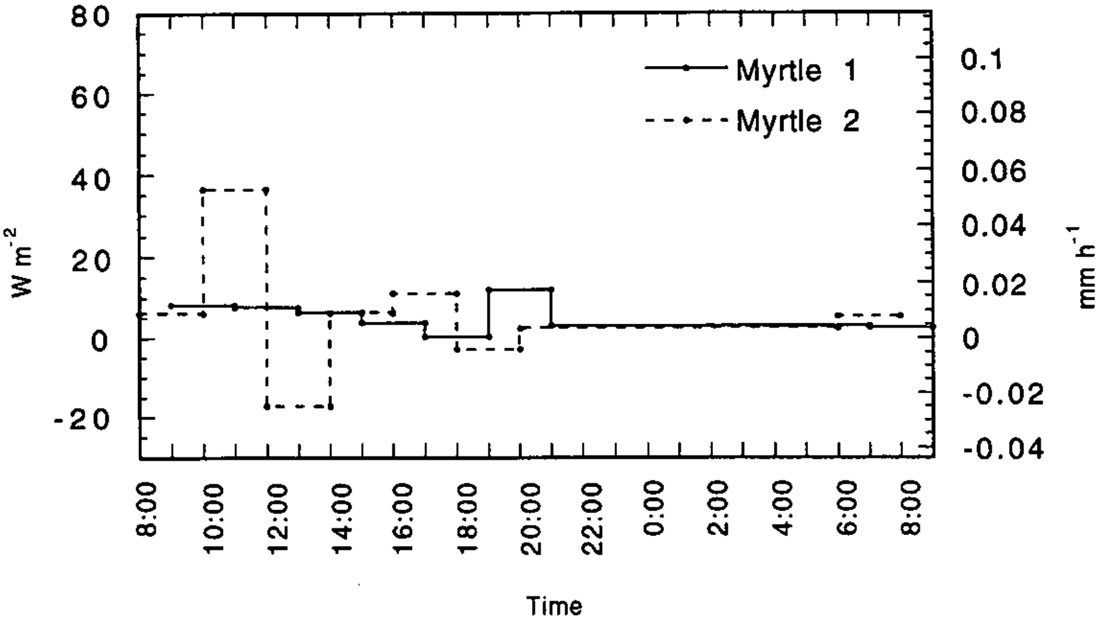

Figure 4.10 Microlysimeter estimates of Q_{Es} during indicated time intervals on May 23-24 at Myrtle 1 and Myrtle 2.

The occurrence of dewfall indicates a vapour gradient directed towards the forest floor and possibly that the forest floor temperature was lower than the air above, causing the near surface air to cool beyond the dew point. The air would then have become saturated causing water vapour to condense as dew on the surface. The cool temperature, lack of air movement and moist soil in the 10 year old forest probably all contributed to the formation of dewfall.

Q_{Es} values at Myrtle 2 during the middle of the day showed great variation, changing from quite strongly positive to negative in consecutive measurements. The occurrence of apparent dewfall in the middle of the day is anomalous, considering that Q^* at this time of the day was at its peak. Dewfall between 12:00 and 14:00 was equivalent to a deposition of 0.05 mm of water. Over the course of the observation period, the fluctuating Q_{Es} values counteracted each other to produce relatively low overall evaporation. There is no apparent explanation for this negative Q_{Es} in the middle of the day.

The average night time value of Q_H was calculated at Myrtle 2 as a residual of the energy balance equation using measured values of Q_{Es}, Q^* and Q_G (Figure 4.11). It was found that the average value of Q_H was -40 W m^{-2}, which is equivalent to about 95% of the net radiative loss. Even when allowing for error, the energy balance equation indicates a strong downward flux of sensible heat towards the surface and this may provide some of the energy necessary to support $Q_{E_s} > Q^*$.

The highest Q_{E_s} measurement at Myrtle 1 was recorded during the night. As on previous runs, evaporation during the night could have resulted from the transfer of heat from the canopy to the forest floor in combination with a strong forest floor-to-atmosphere vapour gradient.

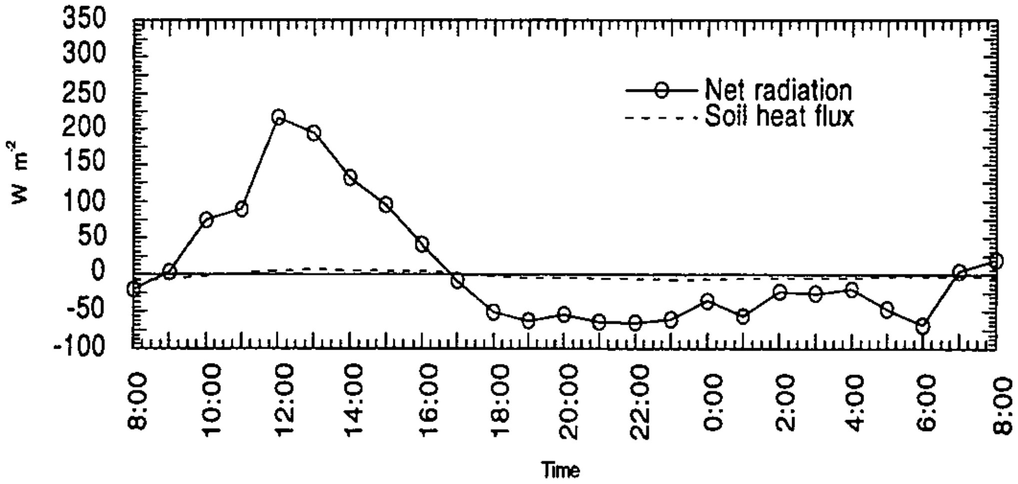

Figure 4.11 Net radiation and soil heat flux at Myrtle 2 for May 23-24

During the May 23-24 measurement run, the soil, and in particular the leaf litter, were moister than on previous measurement runs. Because of this, and given the energy available for evaporation, it would have been expected that Q_{E_s} values would have been much higher than those measured. This suggests that during the winter months, evaporation from the forest floor in re-growth and old-growth forest is limited by the availability of energy.

4.3.4 July 7-8 measurements

On July 7-8 the sky was continuously overcast. Temperatures were particularly low during this measurement period, ranging between 2 and 4 °C. Maximum and minimum temperatures at Myrtle 1 and Myrtle 2 were very similar, with temperatures at Myrtle 1 being marginally higher (Figures 4.2 and 4.3). Soil moisture contents were also very similar at the two sites (Figure 4.4), with slightly more moisture in the soil at Myrtle 2. Leaf litter was observed to be quite moist at both sites. Once again, windspeed beneath the canopy was negligible.

Despite the low temperatures and low Q^* (Figure 4.13) experienced during this measurement run, evaporation was at times relatively high (Figures 4.12). Q_G remained slightly negative for most of the measurement run, indicating a net loss of heat from the soil. At Myrtle 2, Q_{Es} was positive throughout the day and then became negative around sunset. After sunset Q_{Es} once again returned to positive values. The relatively high evaporation experienced at both sites during the day could have been caused by the availability of moisture in the damp layer of leaf litter. This moisture is not insulated from available energy or separated from the atmosphere in the way that the soil is, so evaporation is less restricted.

Fluctuating Q_{Es} values were measured during the day at Myrtle 1. Between 15:00 and 17:00 Q_{Es} was greater than 40 W m^{-2}, which is equivalent to an evaporation rate of 0.06 mm h^{-1}. This value then dropped sharply to about -25 W m^{-2} between 17:00 and 19:00. This negative value indicates quite a strong downward flux of water vapour to the forest floor, equivalent to a rate of -0.04 mm h^{-1}.

Once again, the availability of energy is seen as the limitation on evaporation rate during this period. The wet leaf litter and high moisture content of the soil ensured that more than enough water was available for evaporation. This measurement run revealed how the leaf litter, which insulates the soil and restricts the availability of moisture during the warmer months, can provide a source of water for evaporation from the forest floor during the cooler, wetter months.

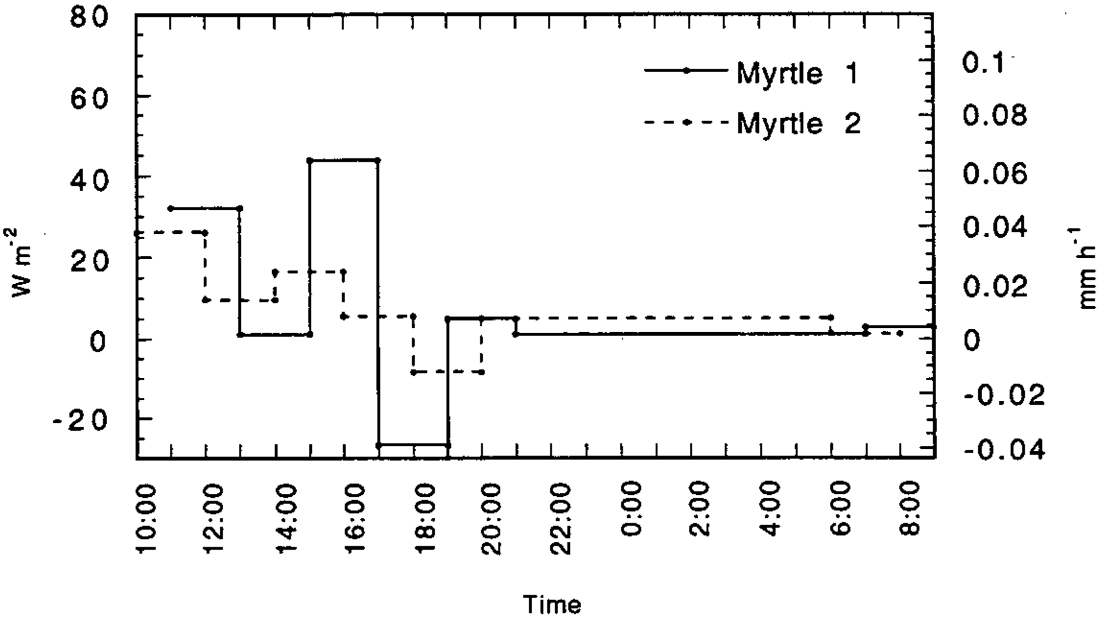

Figure 4.12 Microlysimeter estimates of Q_{Es} during indicated time intervals on July 7-8 at Myrtle 1 and Myrtle 2.

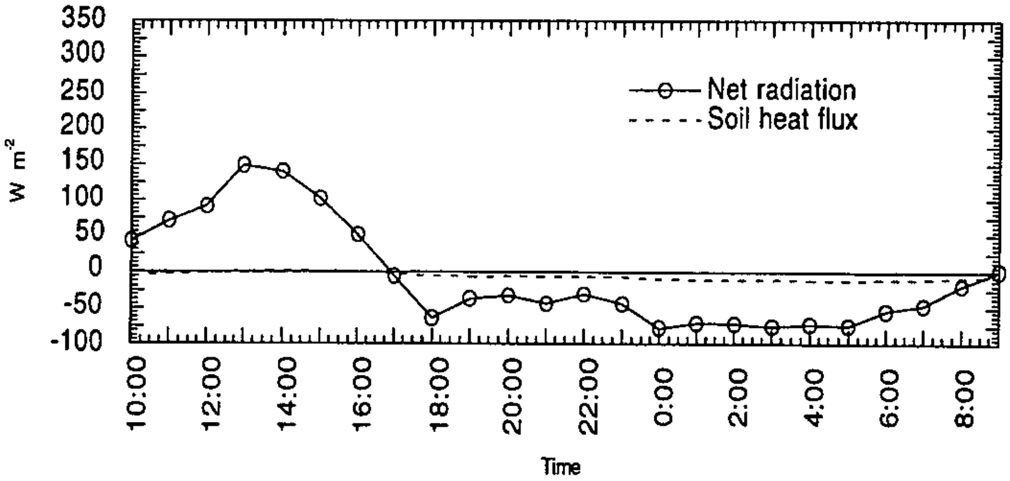

Figure 4.13 Net radiation and soil heat flux at Myrtle 2 for July 7-8.

4.3.5 October 9-10 measurements

On October 9, clear sky conditions prevailed for the day and night but cloud cover developed early the next day. Temperatures ranged between 7 and 14 °C, with slightly higher maximum and minimum temperatures at Myrtle 1 (Figures 4.2 and 4.3). Windspeed above the canopy increased late on October 9, with elevated windspeed continuing into October 10. Consequently, air movement below the canopy was observed to increase during this time. Although air movement was still quite low at Myrtle 2, it was faster and more continuous than at Myrtle 1 where air movement tended to occur in periodic gusts.

Q_{Es} was generally greater at Myrtle 2 than it was at Myrtle 1, particularly on October 10 (Figure 4.14). On October 10, the increased air movement below the canopy at Myrtle 2 caused Q_{Es} to reach 80 W m^{-2} (0.12 mm h^{-1}), which is considerably greater than the highest value during any previous measurement period. Less dewfall was experienced at Myrtle 2, presumably because of the stronger wind speed at this site.

Sufficient data were collected during this measurement run to enable comparison of Q^* and Q_G beneath the re-growth and old-growth forest. The results of this comparison (Figures 4.15 and 4.16) show that, despite the vastly different structures of the 10 and 235 year old mountain ash forest, Q^* and Q_G were similar in both diurnal pattern and maximum values. One noticeable difference between the two sites was the drop to negative Q^* values soon after sunset at Myrtle 1, while at Myrtle 2, Q^* and Q_G remained positive until around 22:00. Q^* is likely to have stayed positive for longer at Myrtle 2 because of more efficient trapping of longwave energy by the canopy.

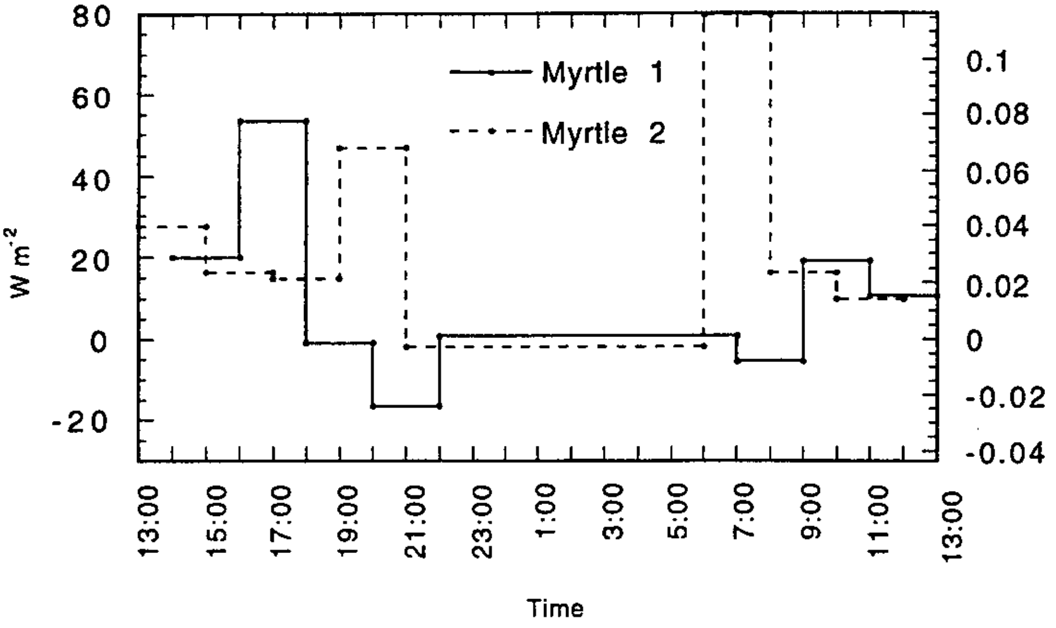

Figure 4.14 Microlysimeter estimates of Q_E, during indicated time intervals on October 9-10 at Myrtle 1 and Myrtle 2.

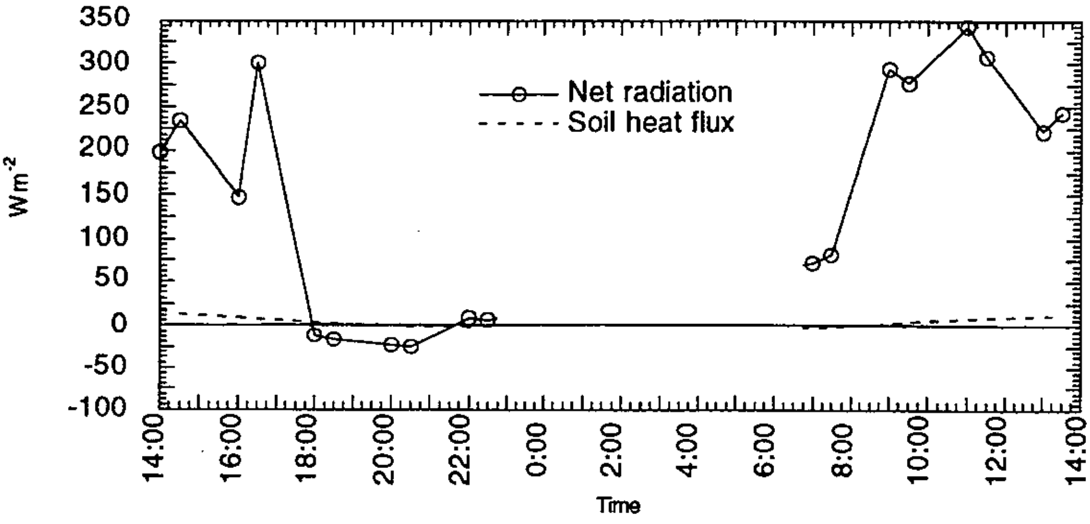

Figure 4.15 Net radiation and soil heat flux for October 9-10 at Myrtle 1.

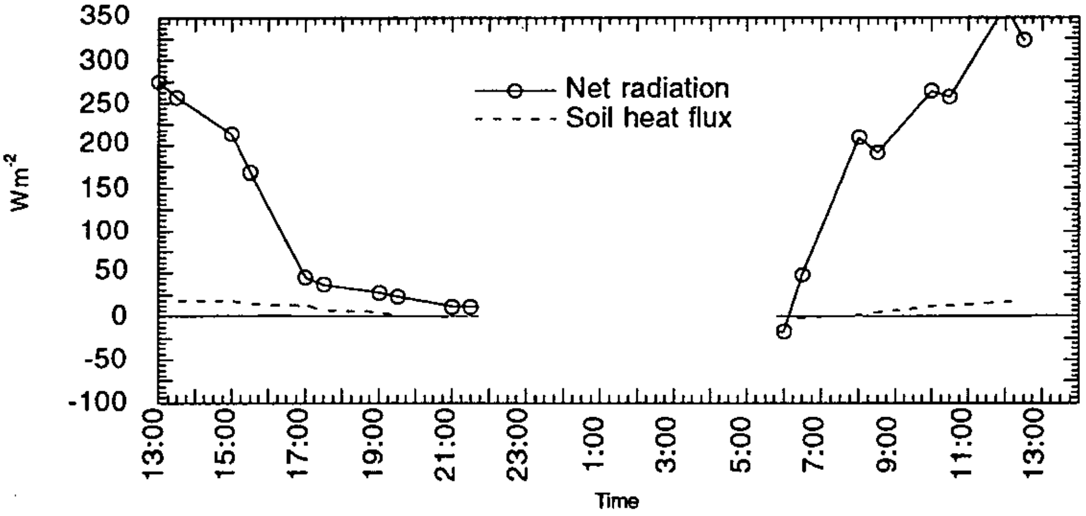

Figure 4.16 Net radiation and soil heat flux for October 9-10 at Myrtle 2.

Vapour pressure at Myrtle 1 showed a similar pattern to Q_{Es} as a result of the input of vapour to the atmosphere through transpiration and evaporation from the forest floor(Figure 4.17). At Myrtle 2, little diurnal variation in vapour pressure was observed (Figure 4.17), presumably because of stronger and more constant windspeed at this site. Therefore, vapour pressure may have been controlled by larger scale processes rather than local evapotranspiration.

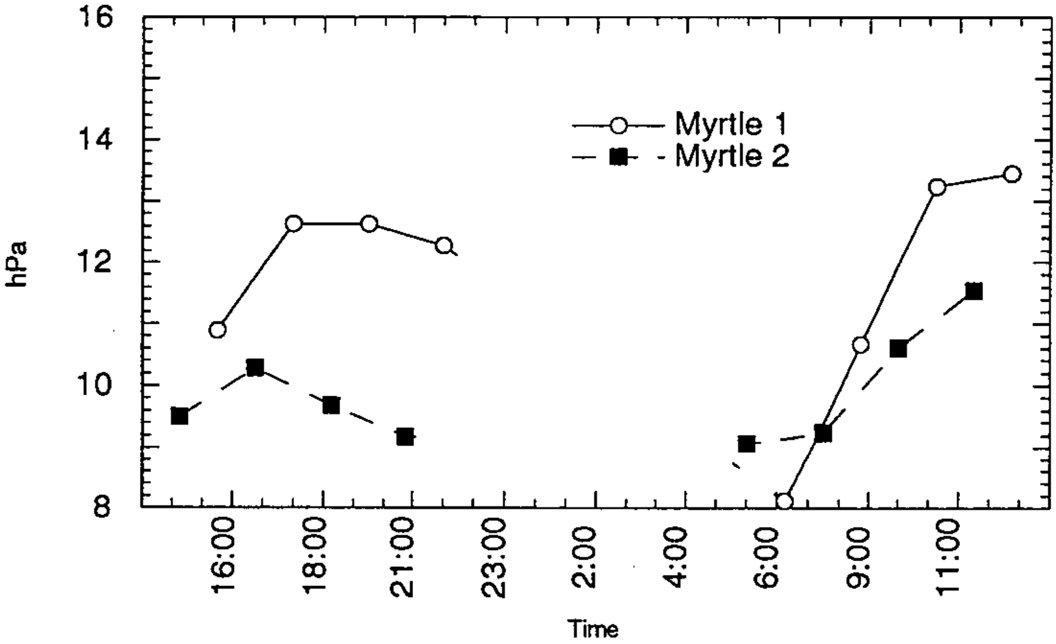

Figure 4.17 Vapour pressure during indicated time intervals on October 9-10 at Myrtle 1 and Myrtle 2.

During this measurement run Q_{Es} variations were largely controlled by the differences in windspeed beneath the canopy at the two sites. The distance from the canopy to the forest floor was responsible for the observed differences in air motion. The large distance from the top of the canopy to the forest floor at Myrtle 1, and the drag imposed by both the overstorey and understorey, kept windspeed at this site to a minimum.

4.4 Estimated annual evaporation from the soil and litter in re-growth and old-growth mountain ash forest

In this section, the Q_{Es} measurements taken throughout the year, will be used in a first-order estimation of annual Q_{Es} (mm year^{-1}) from beneath 235 and 10 year old mountain ash forest. Before this is done, the daily Q_{Es} rates determined by both the microlysimeters and evaporation dome during each of the measurement runs will be compared to evaluate the agreement between these two methods.

The estimates will also be compared with published interception and transpiration rates for mountain ash forest.

4.4.1 Comparison of Q_{Es} measurements taken by the evaporation dome and microlysimeters

The Q_{Es} measurements taken by the microlysimeters and evaporation dome were averaged over each 24 h measurement period and converted to hydrologic units and expressed as an equivalent depth of evaporated water for each day (Figure 4.18).

Figure 4.18 shows that the evaporation dome measured daily Q_{Es} rates that were consistently larger than those measured with the microlysimeters. During May, July and October, the evaporation dome measurements were on average 3.5 times greater than the microlysimeter measurements. Hence the agreement established between these techniques during the Wagga Wagga comparison (Chapter 3) was not repeated beneath the mountain ash forest. The reason for this is believed to be the differences in windspeed at these two locations, that were not adequately replicated beneath the dome.

Within the forest, ground level air movement was very limited and, even when using the slowest fan speed, air movement inside the dome was far greater than it was on the outside. It is thought that the faster air movement inside the dome forces evaporation to proceed at a faster rate. When the evaporation dome is lowered onto the forest floor the increased air motion created by the fans causes the near surface water vapour to be mixed within the evaporation dome, rapidly increasing internal humidity. Therefore, water vapour is moved away from the forest floor at a faster rate than is naturally occurring. This probably explains why Q_{E_s} estimates made by the evaporation dome are too high. At Wagga Wagga, air movement over the bare open soil was much faster, so air movement within the evaporation dome was probably more representative of local windspeed. This would explain the better agreement between the two techniques at this site.

In addition, the evaporation dome is also likely to overestimate Q_{E_s} because it does not measure dewfall. When the evaporation dome is placed on the forest floor the soil and litter is separated from the moisture source above, air motion is induced, and as a result evaporation is measured instead.

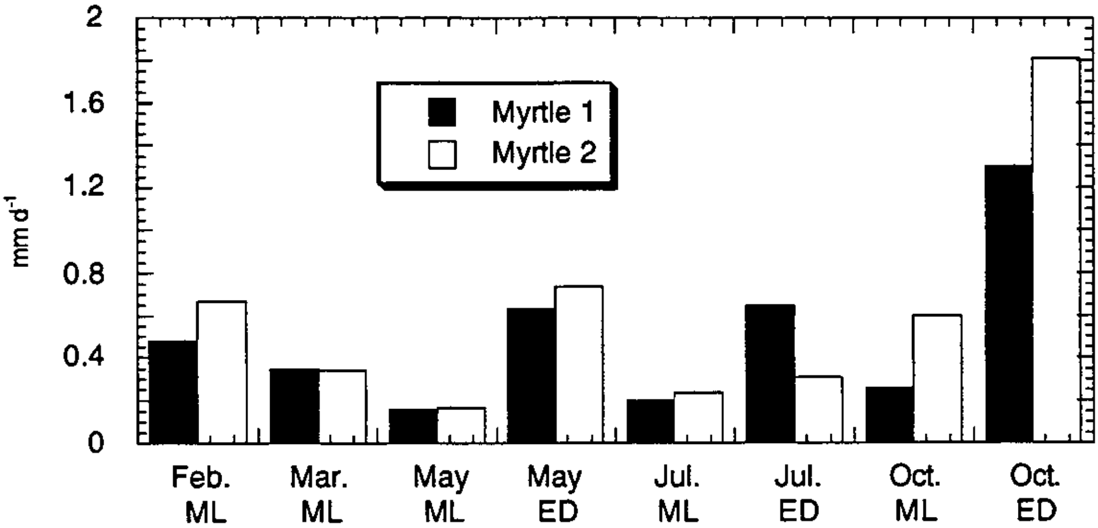

Figure 4.18 Daily Q_{E_s} rate as determined from the evaporation dome (ED) and microlysimeters (ML) for the indicated measurement period.

According to the microlysimeter measurements, daily Q_{E_s} rates in the 10 year old forest are higher than those in the 235 year old forest for all but the March measurement run where the difference was minimal. On days when air movement within the forest was negligible, the differences between Q_{E_s} rates in the 235 and 10 year old forest were very small. During the February run and, in particular, the October run, the observed greater air movement at Myrtle 2 resulted in daily Q_{E_s} rates that were much higher than at Myrtle 1.

Table 4.2 shows representitive maximum, minimum and average weight loss from 20 microlysimeters during the course of our study. The greatest difference between the maximum and minimum weight loss for the indicated runs is just over 0.5 g. The similarity in weight losses from the 20 microlysimeters is also demonstrated by the low standard deviations. The scales used in this investigation were calibrated before the first measurement run and were then cross-checked against a set of laboratory scales at the end of the measurement runs. The cross-checking showed that there was no difference between weights recorded by the two sets of scales.

Run	**Site**	**Time**	**Max. loss (g)**	**Min. loss (g)**	**Av. loss (g)**	**S.D. (g)**
May 23-24	Myrtle 2	1400-1600	0.29	-0.02	0.10	0.08
Feb. 14-15	Myrtle 1	0130-0630	0.39	0.08	0.26	0.10
July 7-8	Myrtle 1	1500-1700	1.05	0.55	0.72	0.14
Mar. 11-12	Myrtle 1	1500-1700	0.61	0.16	0.33	0.15
Oct. 9-10	Myrtle 2	0600-0800	1.55	1.12	1.31	0.12
Feb. 14-15	Myrtle 2	1230-1330	0.79	0.22	0.47	0.14

Table 4.2 Comparison of representitive weight loss characteristics of the 20 microlysimeters used for the indicated time interval.

Because the evaporation dome is thought to be overestimating evaporation, only the microlysimeter measurements have been used for calculating annual Q_{E_s} in the following sections. However, it should be noted that the evaporation dome confirmed the higher rates of evaporation in the 10 year old forest during three of the four measurement runs in which it was used.

4.4.2 *Estimated annual Q_{E_s} in 235 year old mountain ash forest*

Table 4.3 shows the values used to estimate annual Q_{E_s} at Myrtle 1 by extrapolation from the measurements in this study. The calculated rate of 108.3 mm year^{-1} is considered to be an overestimate of Q_{E_s}, because most of the measurements were taken during fine weather conditions. It is also possible that clear weather conditions caused the microlysimeters to overestimate Q_{E_s} as was thought to be the case with during the Wagga Wagga experiment. It should also be acknowledged that the estimated annual Q_{E_s} rate has been calculated from measurements taken on only five days. Despite these caveats, such estimates in both the 235 and 10 year old forest will give a first-order approximation of Q_{E_s} and its relation to forest age. These estimates are the first reported for mountain ash forest.

Measurement run	Q_{Es} mm day^{-1}	Time period applied to	Total Q_{Es}
February	0.48	Dec., Jan., and Feb.	43.2 mm
March	0.35	Mar. and Apr.	21.0 mm
May	0.16	May and Jun.	9.8 mm
July	0.20	Jul., Aug. and Sep.	18.4 mm
October	0.26	Oct. and Nov.	15.9 mm
			108.3 mm year^{-1}

Table 4.3 Calculation of total Q_{Es} at Myrtle 1 during 1995.

Measurements of transpiration from mountain ash trees and the dominant understorey species in 230 year old forest were made over two summer periods (January 1990-April 1990, and October 1990-April 1991) by Dunn and Connor (1993). No measurements were made during the April-October winter period. They reported average transpiration rates of 0.81 mm day^{-1} for 230 year old mountain ash trees and 0.26 mm day^{-1} for the dominant understorey species. These values translate to annual transpiration of around 390 mm year^{-1}. Interception in 230 year old forest has been measured by Haydon *et al.* (in press). They found that the evaporation of intercepted rainfall accounted for about 20% of gross annual rainfall which is equivalent to 325 mm year^{-1}. Combining these measured interception and transpiration rates with the annual Q_{Es} determined in this investigation, gives an evapotranspiration rate of around 820 mm year^{-1}, which is roughly 50% of the average gross annual rainfall. Therefore, it is estimated that Q_{Es} beneath 235 year old mountain ash forest accounts for about 13% of evapotranspiration.

Using the Topog_Yield water balance model, Vertessy *et al.* (1993) predicted annual transpiration, interception and Q_{Es} rates in 230 year old mountain ash forest for 12 years from 1972 to 1983. Their predictions of Q_{Es} gave an annual average of 172 mm year^{-1}, which was equivalent to 24% of the predicted average annual evapotranspiration. This value is significantly greater than our field estimate of 108 mm year^{-1}.

4.4.3 Estimated annual Q_{Es} in 10 year old mountain ash forest

Annual Q_{Es} for Myrtle 2 was calculated in the same way as for Myrtle 1. Once again, the estimated evaporation of 149.8 mm year^{-1} is thought to be an overestimate due to the clear weather conditions prevailing during measurement runs. As in the 235 year old forest, the estimated annual Q_{Es} rate beneath the 10 year old forest has been calculated from measurements taken on only five days during the year (Table 4.4).

Vertessy *et al.* (1996) used a physically based ecohydrological model, Topog-IRM, to simulate overstorey and understorey transpiration, interception, and soil evaporation for a twenty year period following clear felling in the mountain ash forested Picaninny catchment. They predicted that in a 10 year old forest, overstorey and understorey transpiration was 611 and 117 mm year^{-1}, respectively, interception was 177 mm year^{-1} and soil evaporation was 140 mm year^{-1}. The model of Vertessy *et al.* (1996) showed strong agreement between observed and predicted runoff values, therefore, the predicted evapotranspiration must approximate real evapotranspiration. Combining the overstorey and understorey transpiration rates and interception rate of Vertessy *et al.* (1996) with Q_{Es} estimated in this investigation, gives an estimated annual evapotranspiration rate of 1055 mm. Therefore, Q_{Es} beneath 10 year old mountain ash forest is estimated to account for about 14% of annual evapotranspiration.

The predicted rate of soil evaporation of 140 mm year^{-1} by Vertessy *et al.* (1996), compares favourably with our predicted rate of 150 mm year^{-1}.

Measurement run	**Q_{Es} mm day^{-1}**	**Time period applied to**	**Total Q_{Es}**
February	0.67	Dec., Jan., and Feb.	60.3
March	0.34	Mar. and Apr.	20.4
May	0.17	May and Jun.	10.4
July	0.24	Jul., Aug. and Sep.	22.1
October	0.60	Oct. and Nov.	36.6
			149.8 mm year^{-1}

Table 4.4 Calculation of total Q_{Es} at Myrtle 2 during 1995.

4.5 SUMMARY

Q_{Es} beneath 10 year old and 235 year old mountain ash forest was estimated to be about 150 mm and 110 mm year^{-1}, respectively. Using typical transpiration and interception rates determined from other research in mountain ash forests, Q_{Es} was estimated to account for about 13% of evapotranspiration in 235 year old forest, and about 14% of evapotranspiration in 10 year old forest. Although there is little difference between the percentage of evapotranspiration accounted for by Q_{Es} in the two ages of forest, annual Q_{Es} in the 10 year old forest is 27% higher than in the 235 year old forest. Based on these findings, we conclude that forest age appears to be an important determinant of Q_{Es} beneath mountain ash forest. Other investigations in a variety of different forests (Kelliher *et al.* 1992, Denmead 1984, Lafleur and Schreader 1994) have found that Q_{Es} accounts for between 10 and 30% of stand evapotranspiration. Our measurements in mountain ash forest support these findings.

We believe that the Q_{Es} differences observed at the two sites are mainly attributable to differences in windspeed and energy balance characteristics of the forests. The structure of both the 10 year old and 235 year old forest greatly reduced below-canopy windspeed which can have a major influence on forest floor evaporation. In the 235 year old forest, ground level air movement was suppressed to a greater degree than in 10 year old forest. This is due to a combination of the large distance (up to 80 m) between the top of the canopy and the forest floor and further reduction of windspeed by the dense understorey. When faster air movement was observed in the 10 year old forest, daily Q_{Es} rates were found to be up to 50% higher than in 235 year old forest.

The forest structure also had an important influence on night time Q_{Es} values. The dense canopy in the 10 year old forest provided a heat storage area which was a lot closer to the forest floor than in the 235 year old forest. This allowed for more efficient downward flux of sensible heat from the canopy to the forest floor, where part of this energy was used for evaporating soil and litter moisture. The lower and denser canopy in the 10 year old forest also enabled more efficient trapping of longwave radiation released during the night.

During the warmer months, the availability of soil moisture appeared to limit Q_{Es}. Although there was sufficient moisture in the soil for greater Q_{Es}, the moisture was insulated from the available energy by a thick dry litter layer. In the colder months the availability of energy limited Q_{Es}. Over winter, the litter and soil were quite moist but Q^* was low.

During October, Q^* in the re-growth and old-growth forest was compared. It was found that Q^* reached similar maximum values at both sites. Q^* in the 10 year old forest remained positive well into the night, while in 235 year old forest, it became negative soon after sunset. The positive nocturnal Q^* values in the 10 year old forest probably resulted from the trapping of longwave radiation within the canopy.

The evaporation dome was found to overestimate daily Q_{Es}. The reason for this is thought to be that the fans cause air motion inside the dome to be greater than that outside. This causes water vapour to be moved away from the forest floor at a faster rate than is naturally occurring, so Q_{Es} was overestimated. Also contributing to this overestimation of Q_{Es} was the fact that the evaporation dome did not measure dewfall.

5. CONCLUSIONS

5.1 Evaluation of evaporation measurement techniques

Field comparison of the evaporation dome and microlysimeter evaporation measurements with micrometeorological techniques showed that there was reasonable agreement between all methods. Good agreement between methods was found when net radiation was low. Therefore, the low net radiation environment found beneath mountain ash forest places increased confidence in the accuracy of soil and litter evaporation measurements made with the evaporation dome and microlysimeters. However, as has been shown, this agreement was not observed within the mountain ash forest. Reasons for this are suggested later in this chapter.

Although the microlysimeter and evaporation dome techniques are labour intensive, they offer simple cost effective methods for determining evaporation that are not subject to the limitations associated with micrometeorological techniques.

5.2 Soil and litter evaporation beneath re-growth and old-growth mountain ash forest

Q_{Es} beneath mountain ash forest appeared to be influenced by forest age. During all but one of the measurement runs, greater Q_{Es} was measured in the 10 year old forest than in the 235 year old forest. The observed difference is thought to be related to differences in forest structure. The structure of 235 year old forest caused greater reduction in near surface windspeed than was the case in the 10 year old forest. Windspeed was never great at either site, but during two of the measurement runs slightly faster air movement was observed in the 10 year old forest and this is thought to be the cause of the higher Q_{Es} measured on these occasions. The dense canopy in the 10 year old forest provided a more efficient heat storage area which was closer to the forest floor than in the 235 year old forest. This is thought to have promoted more efficient downward transport of heated air from the canopy to the forest floor. The downward flux of sensible heat combined with the trapping of longwave radiation is thought to have contributed to the higher night Q_{Es} which was measured in the 10 year old forest.

Evaporation from the soil and litter beneath 235 and 10 year old mountain ash forest was estimated to be 150 mm year^{-1} and 110 mm year^{-1}, respectively. By combining these estimates with transpiration and interception rates for mountain ash forest which are reported in the literature, it was calculated that soil and litter evaporation in 235 year old forest accounted for 13% of annual evapotranspiration, while in 10 year old forest it accounted for 14% of annual evapotranspiration. Although evaporation from the soil and litter was greater in the 10 year old forest than in the 235 year old forest, it did not account for a much larger percentage of annual evapotranspiration. This is because the transpiration rate was much greater in 10 year old mountain ash forest. As more transpiration measurements are made in mountain ash forest of different ages it will become possible to make better estimations of the percentage of evapotranspiration accounted for by soil and litter evaporation.

Throughout the year, Q_{Es} in mountain ash forest appeared to be restricted by soil moisture and radiant energy. It appeared that during the warmer months the moisture within the soil was decoupled from available energy by a dry layer of litter, while in cooler months soil and litter moisture was plentiful but evaporation was limited by the lack of radiant energy.

Although good agreement was observed between evaporation measurements taken by the evaporation dome and microlysimeters at Wagga Wagga, such agreement was not observed beneath mountain ash forest. Comparison of measurements made by the evaporation dome and microlysimeters within the forest showed that the evaporation dome was overestimated daily Q_{Es}. The forcing of evaporation by faster fan-assisted air movement inside the evaporation dome was thought to be the cause. Despite these findings, the evaporation dome shows potential as a simple method for determining evaporation.

Microlysimeters were found to be a simple but robust method for determining Q_{Es}. The use of a number of microlysimeters allowed the spatial variability of evaporation and dewfall beneath mountain ash forest to be accounted for.

5.3 Implications of results

This investigation represents the first attempt to measure Q_{Es} in re-growth and old-growth mountain ash forest. A greater insight into the processes controlling Q_{Es} in mountain ash forest was gained.

This investigation has dealt with a component of forest hydrology and meteorology that has received little attention to date. Evaporation from the soil and litter beneath forest is often neglected in hydrological and meteorological studies due to the perceived lack of importance of this component and the limited availability of measurement techniques.

This investigation found that Q_{E_s} was important in the catchment water balance of mountain ash forest, and contributed significantly to total stand evapotranspiration. This investigation has also outlined the importance of forest age in determining Q_{E_s}. As the forest ages, its structure changes and this appears to influence energy exchanges and the climate near the forest floor, which in turn determines Q_{es}.

Q_{E_s} does not show the same relation with forest age as water yield does in the Kuczera curve (Figure 1.1). It appears more likely that Q_{E_s} will slowly decline as the mountain ash forest matures. Q_{E_s} is likely to be greatest when the forest is in the initial stages of regeneration. During this time the soil, which would be expected to have a higher moisture content due to reduced root uptake, would be exposed to the wind and sun and Q_{E_s} would be expected to be high. As the mountain ash forest becomes established, transpiration is expected to increase in importance and air movement and solar radiation at the forest floor level are expected to be reduced with canopy development, resulting in a decrease in Q_{E_s}. With further forest growth the distance between the active surface and the forest floor increases, and this limits the transfer of energy to the soil and litter from above. When the forest reaches maturity, the canopy opens up but a dense understorey develops ensuring that solar radiation at the soil and litter level remains low. As observed in this investigation, the structure of mature mountain ash forest is such that air movement at the forest floor level is less than in re-growth forest, so reduced transport of water vapour away from the soil and litter surface also contributes to reduced Q_{es}.

The measurements taken in this study will provide the only means to date for validating catchment predictions of Q_{E_s} made by the Topog water balance models (Vertessy *et al.* 1993, Vertessy *et al.* 1996). If acceptable agreement between observed and predicted values is not achieved, further measurements of Q_{E_s} in a range of different age forests may be needed. From these measurements it may be possible to develop a numerical relationship between Q_{E_s} and forest age which could be incorporated into Topog to improve its predictive capabilities. With further improvement of this model and a better understanding of catchment processes, reduction of the error bands associated with the Kuczera curve may be possible.

5.4 Further research

Results from this investigation suggest that the evaporation dome needs to be further tested and modified before confidence in its accuracy can be achieved. It is hypothesised that the reason why the evaporation dome produced overestimates of evaporation is that the four speed fan control does not allow accurate enough approximation of the external windspeed. Tests need to be carried out to see how the estimated evaporation rate is affected by the selected fan speed. If these tests prove the hypothesis to be correct, the four speed fan control will need to be replaced with a rheostat (dimmer switch) which will make it possible to continuously vary internal windspeed to match the external windspeed. The internal and external windspeed can be determined with a small but sensitive anemometer.

The effect of the plexiglass dome on the transmittance of net radiation and, more specifically, the transmittance of longwave and shortwave radiation also needs to be assessed to determine if the evaporation dome significantly alters internal radiation.

Future measurements of soil and litter evaporation in mountain ash forest would benefit from measurements of net radiation at each site and in the open. This would enable the alteration of net radiation by mountain ash forest of different ages to be assessed. Measurements of litter moisture content, as well as soil moisture content, could also help in the explanation of observed evaporation from the forest floor. In this investigation it was found that even slight variations in windspeed between sites caused relatively large differences in evaporation. Therefore, it is felt that future research would benefit from the use of accurate measurements of windspeed using low-threshold anemometers. Measurements of surface temperatures with an infrared thermometer could also provide a means of accounting for observed Q_{Es} values.

Further investigation into soil and litter evaporation from beneath mountain ash forest of a variety of different ages is likely to occur in the future. It is hoped that modifications to the evaporation dome will allow rapid soil and litter evaporation measurements to be made, without the need for microlysimeters, thus greatly reducing the labour intensity of the 24 h measurement runs.

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COOPERATIVE RESEARCH CENTRE FOR
CATCHMENT HYDROLOGY

Centre Office
Department of Civil Engineering, Monash University, Clayton, Victoria 3168, Australia.
Telephone: (03) 9905 2704 Facsimile: (03) 9905 5033 International: +61 3 9905 2704
http://www-civil.eng.monash.edu.au/centres/crcch/