Comparing micrometeorology of rain forests in Biosphere-2 and Amazon basin

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Abstract

Micrometeorological variables measured in the BIOSPHERE-2 Center (B2C) enclosed rain forest biome for 1 year were compared with similar measurements made in the Amazon rain forest. In the B2C rain forest, the overlying glass and supporting structure significantly reduces (by approximately a factor of two) the incoming solar radiation. Monthly mean values of above-canopy and within-canopy air temperature, vapor pressure, and vapor pressure deficit are reasonably similar to those of the Amazon rain forest, but there are marked differences in the above-canopy values of these variables in the Arizona summer. Monthly mean diurnal trends also show significant differences. Measurements of vertical air temperature gradient clearly showed two very distinct environments in the 27.4 m high rain forest dome during daylight hours. There is a comparatively cool and fairly well-mixed environment (which is reasonably similar to that found in a natural rain forest) below about 10 m and a hot, thermally stable environment above about 15 m. The nature of the atmospheric turbulence within the B2C rain forest is also significantly different from that normally found in natural rain forests. There is little turbulent mixing above the forest canopy in this enclosed environment. These findings are important for guiding the operation and use of this experimental rain forest facility in future research and for understanding how the rain forest biome functions in an enclosed environment. ©2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Observations show that, over the last 100 years, atmospheric carbon dioxide (\(\text{CO}_2\)) concentration has increased by about 70 ppm (Schimel et al., 1996) and global average near-surface air temperature has increased by 0.7–0.9°C (Nicholls et al., 1996). The increase in atmospheric \(\text{CO}_2\) concentration has been caused mainly by fossil fuel emissions and land-use changes in the tropics and subtropics (Intergovernmental Panel on Climate Change, Houghton et al., 1996). Recent studies suggest that tropical rain forest ecosystems are a major sink for fossil fuel carbon (Grace et al., 1995). However, our current understanding of the functioning of these forest ecosystems does not allow accurate prediction of their carbon...
sink and sources strength because it is not known how these ecosystems will respond over time to changes in atmospheric CO2 and global warming.

The enclosed tropical rain forest ecosystem at the Columbia University BIOSPHERE-2 Center (B2C) potentially offers the opportunity to understand the functioning of tropical rain forests and test models of their interaction with the overlying atmospheres in a controlled, well-documented, CO2 -enriched environment. In principle, understanding the functioning of the B2C rain forest can be used to test the formulations used to parameterize rain forest vegetation in the land-surface–atmosphere interaction schemes used in weather and climate prediction models. However, to place the ensuing understanding in proper context, it is necessary to evaluate how representative are the meteorological conditions in the B2C rain forest relative to those prevalent in the earth’s natural rain forests. This paper describes a field study that was conducted in the B2C’s rain forest biome to make micrometeorological measurements over a 1-year period. These data were compared with equivalent measurements at three forested sites in the Amazon River basin in Brazil. Data from the Anglo Brazilian Amazonian Climate Observational Study (ABRACOS: Shuttleworth et al., 1991; Gash et al., 1996) were used to provide the basis for comparison.

2. Materials and methods

2.1. The BIOSPHERE-2 rain forest biome

The B2C (32°34′N, 110°51′W, elevation 1200 m, area 1.25 ha) is located near Oracle, AZ, USA. The structure is constructed of sealed glass (two 6 mm panes of glass with thin plastic laminate between) and space frame (ASTM 8500 grade B tube struts, 6 cm in diameter (Fig. 1a)). It houses samples of some of the earth’s most important biomes, such as rain forest, desert, savanna, and oceans. To the extent possible, temperature, humidity, rainfall, CO2 content, and other environmental variables are controlled.

The B2C tropical rain forest enclosure covers 1900 m² and is 27.4 m high at its highest point. Different habitats are recreated within the B2C rain forest biome, namely lowland rain forest, a ginger belt (1–4 m wide dense belt of vegetation surrounding the rain forest on three sides to shield the understorey from excessive sunlight), a bamboo belt (to precipitate any airborne salt particles coming from the adjacent ocean biome on the southern side), varzea (an area periodically flooded for extended periods), surface water ponds, a stream, and mountain terraces. The lowland rain forest is the largest and tallest habitat represented and is considered to be typical of a wet equatorial forest. The dominant plant species in the lowland rain forest are Ceiba pentandra, Hura crepitans, Cecropia peltata, Arenga pinnata, and Clitoria racemosa. At this location, the canopy height is approximately 12–13 m. However, a few trees, such as Ceiba pentandra and Arenga pinnata, reach 16–17 m. Plants in the ginger belt biome include Musa, Heliconia, Alpinia, Strelitzia, and Costus. The bamboo belt consists of Bambusa multiplex and B. tuldoides, and the varzea comprises Phytolacca dioica, Pachira aquatica, and Pterocarpus. Plants on the mountain terraces are a mixture of Carica papaya, Clitoria racemosa, Coffea arabica, Panama hat palm, Inga sp., Hibiscus rosa-sinensis, and Strelitzia nicolai. A schematic diagram of the layout of the B2C rain forest is shown in Fig. 1b.

The soils in the B2C rain forest were created from locally available material. There are two layers of soil: topsoil and subsoil. The subsoil layer (a mixture of rock, pebble, and very sandy loam) has uniform composition, but it varies in thickness (0–5 m) to provide gentle slopes. The topsoil consists of a mixture of a local (Wilson Pond) loam with organic and/or gravelly sand in different combinations for each of the rain forest habitats. Soil biota (inocula) were also introduced in the form of undisturbed soil cores, humus, and organic litter (along with earth worms). The B2C rain forest soils were originally very high in organic carbon, but recent studies (Lin et al., 1998) have shown that the current carbon content is within the range typical of natural rain forest soils.

Rainfall typically occurs every fourth day in the B2C rain forest. The primary source of rain is overhead sprinklers mounted near the roof, but some areas are irrigated with ground sprinklers and drip irrigation systems. In addition, water vapor is introduced into the air through a mist system when the relative humidity drops below 75%. Circulation of the air is controlled through six air handlers that
Fig. 1. (a) General view of the BIOSPHERE-2 Center showing the relative position of the rain forest biome in which studies were made. (b) Plan view of the rain forest biome showing structural features in the biome, the positions of the central, north, and southern locations where instruments were mounted, and the points (1, 2, 3, 4, 5) near which soil samples were taken in this study. (c) Schematic cross-section of the rain forest biome showing the vertical position of the sensors used at the central location in this study.
open into the basement of the rain forest. Chilled (or heated) water is passed through the coils of these air handlers to control the temperature and humidity of the air. Air is blown across the forest floor from west to east and returns through gratings on the periphery of the rain forest. The normal temperature range of the air passing through the air handlers is 21–29°C. Because the rain forest atmosphere is connected with the atmospheres in the adjacent desert, savanna, and ocean biomes, there may be some loss of atmospheric humidity into the surrounding biomes (recently installed curtains can now be used to isolate the rain forest atmosphere from adjacent ecosystems). Water condensation occurs on the inside surface of the glass structure during late autumn, winter, and early spring. This condensation and any rain or irrigation water which percolates through the soil is collected and recycled to the rain forest after the removal of dissolved solids using a reverse osmosis system.

2.2. ABRACOS field sites

The ABRACOS provided representative data for forested and deforested areas in different climate zones across the Amazon River basin. Detailed studies of surface climatology, micrometeorology, plant physiology, and soil hydrology were made at three forest and adjacent clearing sites from late 1990 to December 1993, although the automatic weather stations (AWS) continued data collection afterward (Shuttleworth et al., 1991; Gash et al., 1996; Gash and Nobre, 1997). A brief description of each site is given ahead.

The Reserva Jaru forest site (10°50′S, 61°55′W, altitude 120 m) is located 80 km northeast of Ji-Paraná, Rondônia near the southwestern edge of the Amazon forest. In this region, the forest has been progressively cleared over the last two decades in an organized way, resulting in a “fishbone” pattern of clearings. It has pronounced dry periods lasting several weeks between June and August, when the rainfall is less than 10 mm per month. December through April is the wettest season. Meteorological measurements were made on a 52 m high tower. The average tree height is 33 m, but some trees reached 44 m. The soil at the Reserva Jaru forest site is a medium-textured red-yellow podzol (Hodnett et al., 1996).

The Reserva Ducke site (2°57′S, 59°57′W, altitude 80 m) is in a protected forest about 25 km from Manaus, Amazonas in central Amazonia, where there is only limited forest clearing. The driest months (with less than 100 mm rainfall) are June through September, and the wet season is from December through April. Dry periods rarely last more than a week. The mean canopy height is 35 m, but some trees reach 40 m. The meteorological data were collected near the top of a 45 m tower. The soil at this site is a yellow Latosol (Oxisol or Haplic Acrorthox) with 80% fine clay content and high conductivity (Hodnett et al., 1996; Wright et al., 1996).

The Reserva Vale do Rio Doce site (5°45′S, 49°10′W, altitude 150 m) is in a 17 000 ha protected forest located about 50 km south of Marabá, Para, which is surrounded by large clearings. The driest months (with less than 20 mm rainfall) are June through August, and the wet season is from December through April. Meteorological data were collected at the top of a 52 m tower. The soil at the Reserva Vale do Rio Doce site has been classified as a medium-textured, yellowish cambisol (Hodnett et al., 1996).

2.3. Instruments and methods

The instruments used in the B2C rain forest study included two AWS systems that provided routine measurements of meteorological variables, and an eddy correlation (EC) system which provided measurements of the turbulent structure of the atmosphere in the B2C rain forest biome. These instruments were installed on three hanging frames located on the north, center, and south sides of the rain forest (Fig. 1b–c). The frames, which were mounted vertically on ropes, were designed to cause minimum disturbance to the environment inside the rain forest biome. They were 1 m wide and 1.5 m high and made from galvanized iron pipe, with a 0.11 m wide aluminum plate across the bottom which was used to mount the sonic anemometer vertically. The height of the platform could be adjusted to allow micrometeorology measurements at different heights.

One AWS was installed at 15 m above the ground at the so-called ‘central location’ throughout the year, while the second AWS was used for shorter periods at the so-called ‘northern location’ and ‘southern location’ (Fig. 1b) to measure meteorological variables at different heights. The data were logged each second,
then averaged over 15 min intervals using data loggers (Campbell Scientific, UT, USA; model 21X). At the central location, the data were initially averaged at 10 min intervals (from 18 October 1997 through 24 February 1998) but then at 15 min intervals for the remainder of the study. When deployed, the EC system was installed at the central location at different heights within and above the canopy.

2.3.1. Standard meteorological instruments

2.3.1.1. Central location The AWS at the central location provided continuous measurements of net radiation ($R_n$) using a net radiometer (REBS, WA, USA; model Q7); incoming short-wave radiation ($S_i$), and outgoing short-wave radiation ($S_o$) using pyranometers (Epply Laboratory, Newport, RI, USA; model PSP); air temperature ($T_a$) and relative humidity (RH) using a combined sensor (Vaisala, Finland; model HMP35C and HMP45C); air pressure using a pressure transducer (Motorola, AZ, USA; model MPX2200AP), soil temperatures ($T_s$) and soil heat flux (SHF), using two soil thermocouple probes (Campbell Scientific, UT, USA; model TCV A), and one soil heat flux plate (REBS, WA, USA; model HFT-3.1). Measurements were taken from 18 October 1997 to 31 October 1998. $R_n$, $S_i$, and $S_o$ were recorded at 15.2 m, and $T_a$ and RH were recorded at 15.5 m above the ground. $T_s$ and SHF were measured at a location approximately 5 m south of the central location. The SHF plates were buried 0.08 m below the soil. The average temperature above the soil heat flux plates was found by averaging the measured $T_s$ at 0.02 and 0.06 m. On 21 July 1998, a second (HMP45C) probe was installed 7.6 m above the ground at the central location to measure the in-canopy vertical profiles of $T_a$ within and above the canopy between 19 May 1998 and 21 July 1998 (Fig. 1c).

A comparison of $T_a$ measured by one thermocouple and both $T_a$/RH probes installed at 15.2 m height at the central location for 10 days (27 May 1998–5 June 1998) showed that, although the probes agreed well with each other, the thermocouple measurements were systematically lower by 1.1°C at night and by 4.2°C during daylight hours. It is likely that the night-time difference is the result of poor relative calibration between two different types of $T_a$ sensors, while the greater discrepancy during the day may be due to solar heating of the metal screen in which the $T_a$/RH probe is housed. Fortunately, the overall conclusions of the present study are not sensitive to the absolute accuracy of these $T_a$ data, and no attempt was made to re-calibrate the sensors. However, the reader is advised that values of $T_a$ shown later may be prone to absolute errors on the order of a few degree Celsius.

2.3.2. Air temperature profiles

Fine-wire Chromel–Constantan thermocouples (Campbell Scientific, UT, USA; Type E, 0.076 mm diam) were installed 1.5, 4.5, 7.6, 10.6, 15.2, 20, and 26 m above the ground at the central location to measure the vertical profiles of $T_a$ within and above the canopy between 19 May 1998 and 21 July 1998 (Fig. 1c).

A comparison of $T_a$ measured by one thermocouple and both $T_a$/RH probes installed at 15.2 m height at the central location for 10 days (27 May 1998–5 June 1998) showed that, although the probes agreed well with each other, the thermocouple measurements were systematically lower by 1 ± 1°C at night and by 4 ± 2°C during daylight hours. It is likely that the night-time difference is the result of poor relative calibration between two different types of $T_a$ sensors, while the greater discrepancy during the day may be due to solar heating of the metal screen in which the $T_a$/RH probe is housed. Fortunately, the overall conclusions of the present study are not sensitive to the absolute accuracy of these $T_a$ data, and no attempt was made to re-calibrate the sensors. However, the reader is advised that values of $T_a$ shown later may be prone to absolute errors on the order of a few degree Celsius.

2.3.3. Eddy correlation system

The EC system used in this study was developed by Unland et al. (1996) following the design of Moncrieff et al. (1997). Variations in wind velocity were measured using a 3-axis ultrasonic anemometer (Gill
Instruments, Hants, UK; Model 1012R2A) which allows real-time corrections for the flow distortion and wind shadowing generated by the anemometer structure. Variations in CO₂ and water vapor concentrations were measured using a closed-path Infrared Gas Analyzer (IRGA, LICOR, NE, USA; model 6262) which was calibrated once each week against known concentrations of CO₂ and water vapor. Saturated water vapor (generated from a dew-point generator, LICOR, NE, USA; model LI-610) and a compressed reference CO₂ (1060 ppm accurate to 1% of the National Institute of Standards standard) were used to calibrate the IRGA. Scrubbing chemicals (soda lime for CO₂ and Mg(ClO₄)₂ for water vapor) were used to provide air samples with zero concentration. A laptop computer (Hitachi, Japan; model VisionBook, 133 MHz) was used for system control and for online data processing using version 0.39 of the ‘EdiSol’ software (Moncrieff et al., 1997). The process of ducting an air sample from the intake near the sonic anemometer above the canopy to the IRGA introduces a delay of several seconds between the wind vector and concentration measurements. The lag time was determined from a cross-correlation analysis between the measurements of CO₂ and water vapor and \( T_a \) measured by the sonic anemometer. Between 17 June 1998 and 28 July 1998, the EC system was installed at different heights (15, 7.5, and 3 m) above the ground to measure energy fluxes and CO₂ and water vapor fluxes and concentrations at the central location.

2.3.4. Soil moisture

Gravimetric soil-moisture content was measured every 4 weeks on Tuesdays from 26 February through 8 October 1998 at five different locations in the B2C rain forest (but for only two locations in February). These locations are shown in Fig. 1b. Surface soil samples (approximately 150 gm) were collected from 2 cm depth and oven-dried at 110°C for more than 24 h. In addition, two ‘Watermark’ sensors (Campbell Scientific, UT; Model 257L) were installed at depths of 0.05 and 0.85 m near the central location to measure soil water potential. Data from these sensors were collected from 24 February 1998 through 15 May 1998 and from 21 July 1998 through 31 October 1998. Soil temperatures from the nearby soil thermocouples were used in the calculation of soil water potential.

2.4. Data analysis and quality control

There were no significant missing data periods in the AWS record for the B2C rain forest. However, radiation data for the central location are missing from 13 January 1998 through 27 January 1998, because radiation sensors were removed for cross-calibration. Data from each sensor used in the B2C were plotted for checking and quality control after each data download. Hourly, daily, and monthly average values of meteorological variables were calculated from the 15 min data. If three 15 min values were missing during an hour, the hourly average value for that hour was deemed unacceptable. Similarly, if 12 h of data were missing during a 24 h period, the daily average value for that day was deemed unacceptable. Data from missing days were not included when calculating monthly average values, and missing hourly data also were not considered when calculating the mean monthly diurnal cycle for meteorological variables.

Meteorological data from all three ABRACOS sites were available as hourly average values. Daily average, monthly average, and the mean monthly diurnal cycle of meteorological variables were calculated using the same criteria given in the previous paragraph. A 4 h time difference was used to convert the GMT time used in the ABRACOS data to local Arizona time. Monthly average values of meteorological variables from the ABRACOS site were shifted by 6 months when comparing with similar values from the B2C rain forest to compensate for seasonal difference in the climate of the two regions, e.g., B2C data in January were compared with ABRACOS data in July. The reader is advised to bear in mind this 6-month shift when viewing all monthly average and mean monthly diurnal plots from the ABRACOS data (e.g., Figs. 2 and 3), although, in fact, there is only limited seasonal change in the climate of the three Amazon sites.

3. Results

3.1. Climate characteristics

3.1.1. Mean climate of BIOSPHERE-2 rain forest biome

The overlying glass and supporting space frame greatly influence the radiation regime in the B2C rain
forest. There is, for instance, a significant difference of about a factor of two between $S_i$ measured inside and outside the biome (not shown). Radiation absorption (approximately 50%) by the B2C glass and space frame is high in comparison with the 10–20% absorption reported for glass greenhouses (Mistriotis et al., 1997) because of the need for (6 cm diam) pipe struts to support the (12 mm thick) glass roof and walls. Over time, dust is deposited on the outer surface of the glass, and organic matter is deposited (by condensation) on the inner surface of the glass which contributes to the reduction in solar energy flux. In addition, dew formation blocks $S_i$ in the early morning. However, the most consistent cause of solar energy loss is shading by the individual pipes that make up the supporting structure. The measured values of $S_i$ taken with radiometers inside the B2C rain forest during this study showed clear evidence of short-term shading by individual components of the supporting structure. However, when measured values are averaged to give the hourly and daily average values reported here, the intermittent nature of shading by support structures is not apparent, and
their effect shows primarily as a net reduction in the average measured value. However, intermittent shading may be significant when considering time-average physiological behavior because individual leaves high in the forest canopy in B2C spend part of the time in bright sunlight and part of the time in shade.

Fig. 2a–l illustrate the comparison between mean monthly values of $S_i$ and $R_n$ in the B2C rain forest biome and 4-year (1991–1994) average values of these variables at the three Amazon rain forest sites. Fig. 2 confirms that there is consistently much less $S_i$ falling on the canopy in B2C than in the Amazon case, typically 75% less in the Arizona winter and 25% less in the Arizona summer. Fig. 2 also confirms that, in the Arizona winter, the $R_n$ in B2C is consistently about 25% of that for the Amazon while, in the Arizona summer, B2C $R_n$ is almost equal to that for the Amazon.

The measured albedo of the rain forest in B2C is around 15%. It is on the average a few percent higher than measured values for the Amazon rain forest. In fact, the albedo of the B2C rain forest is almost equal to the value measured at the ABRACOS Reserva Vale do Rio Doce site, but it is greater than the value measured at the other two ABRACOS sites. [Note: it is possible that the higher-measured value for albedo in B2C shown in February in Fig. 2c is a sampling prob-
lem associated with local, anomalous shading by the supporting structure of the upward-facing radiometers in B2C. The measured values of $S_i$ and $R_n$ for February seem lower than the annual trend would suggest.] Fig. 3a–l show the monthly mean diurnal cycles of $S_i$ and $R_n$, measured above the B2C rain forest and 4-year (1991–1994) average values of these variables measured above the forest at the three ABRACOS sites. The monthly mean diurnal trend of $S_i$ and $R_n$ changes noticeably with season in the case of the B2C rain forest, from typical peak values of about 200 W m$^{-2}$ in December to 400 W m$^{-2}$ in June. For the Amazon rain forest, the monthly average values of measured radiation are reasonably consistent between sites, and there is much less seasonal change. The large difference in above-canopy $S_i$ between B2C and the Amazon generates a large difference in the above-canopy $R_n$ in the Arizona winter. However, in the Arizona summer, the (then smaller) difference in $S_i$ is almost canceled by a net downward long-wave radiation above the canopy. Consequently, the above-canopy $R_n$ in B2C and the Amazon are quite similar. This interesting phenomenon is associated with a pool of hot air that is generated in the space above the canopy in B2C, which is described in greater detail in Section 3.1.2.

Fig. 2 j–r illustrate the mean monthly values of $T_a$, atmospheric vapor pressure (VP) and vapor pressure deficit (VPD) in the B2C rain forest biome in comparison with 4-year (1991–1994) average values of these variables measured at the three Amazon rain forest sites. In terms of monthly mean values, the B2C rain forest environment is reasonably similar to the Amazonian rain forest at all three sites in the Arizona winter, but there is a marked difference in the values of these parameters in the Arizona summer. In the B2C rain forest, monthly mean values of $T_a$, VP, and VPD are typically 27–31°C, 2.8–3.5 kPa, and 0.6–1.5 kPa, respectively, while monthly mean values of these variables in the Amazon rain forest are typically 22–26°C, 2.0–2.7 kPa, and 0.4–1.4 kPa, respectively (see also Culf et al., 1996). The difference between B2C rain forest and Amazon rain forest climate during the summer months occurs because increased radiative heating enlarges the discrepancy for above-canopy $T_a$ and VPD.

Fig. 3m–dd show the monthly mean diurnal cycles of $T_a$, VP, and VPD measured over the B2C rain forest and 4-year average values of these variables over the three Amazon rain forest sites. At all the Amazon sites, the monthly average VP is about 2.5 kPa, fairly constant throughout the day, and similar throughout the year. There is, on the average, typically a 7–10°C diurnal cycle in $T_a$, which also is similar throughout the year and which does not change greatly between sites. There is a marked daily cycle in VPD in the Amazon, with near saturation at night and, on the average, VPD reaching peak values of 1–2 kPa during the day. In the Arizona winter, $T_a$ above the B2C rain forest is broadly similar to the value above the three Amazon sites, but VP is higher during daylight hours, and the daily cycle in VPD is less than for the Amazon sites. In the Arizona summer, the peak values of $T_a$, VP, and VPD above the B2C rain forest are all much larger than above the three Amazon rain forest sites. The reader is reminded that the B2C rain forest data presented in Fig. 3 were recorded above the forest canopy. Subsequent measurements within the B2C rain forest canopy (described later) show that the within-canopy environment is very different from the above-canopy environment in the B2C and is in fact more similar to the within-canopy Amazon rain forest environment, even during the Arizona summer.

### 3.1.2. The vertical gradient of air temperature

Fig. 4 shows $T_a$ measured at 1.5, 4.5, 7.6, 10.6, 15.2, 20, and 26 m above ground level on a typical summer day (22 June 1998) in the B2C rain forest. Fig. 4a shows $T_a$ as a function of height at 6:00, 10:00, and 12:00 hours, while Fig. 4b shows $T_a$ at each measurement height as a function of time of day. Most of the change in $T_a$ occurs between 10 and 15 m. Below 10 m, $T_a$ is fairly constant with height and fairly constant throughout the day. Above 15 m, there is a steady rise in $T_a$ during the morning (presumably resulting from the capture of solar energy by the overlying structure of B2C). Above 15 m, $T_a$ is reasonably constant during the afternoon, but it then falls off rapidly after dusk as the overlying structure cools by radiative (and perhaps convective) cooling processes.

Thus, during the day and early evening, there is a very strong positive gradient of $T_a$ (and consequently a very stable atmosphere) just above the forest canopy. (In fact, in the past, the bubble of hot air has sometimes reached down as far as the top of the forest canopy,
Fig. 4. Air temperature ($T_a$) measured with thermocouple thermometers at 1.5, 4.5, 7.6, 10.6, 15.2, 20, and 26 m above ground level on 22 June 1998 in the Biosphere2 Center (B2C) rain forest at central location. (a) $T_a$ as a function of height at 6:00, 10:00, and 12:00 hours; (b) $T_a$ at each measurement height as a function of time of day.

causing die-back among the highest leaves and stems. However, an improved air-handling system meant that no die-back occurred during this study.) Hence, there are two very distinct temperature environments in the B2C rain forest during daylight hours. B2C has a comparatively cool and reasonably well-mixed environment below 10 m (whose temperature is in fact similar to that of the Amazon rain forest), and a hot, stable environment above 15 m. At night, the $T_a$ in the B2C rain forest biome changes little with height.

3.1.3. Spatial variability of above- and within-canopy meteorology

A study was made of how meteorological variables differ at different locations in B2C and how they change with height through the rain forest canopy.
fairly quiescent body of in-canopy air and the air in the upper region of the B2C rain forest enclosure that is strongly heated during daylight hours.

3.2. Measurements with the eddy correlation system

3.2.1. Turbulent transport

The B2C rain forest biome is clearly not an appropriate site for traditional micrometeorological measurements, but data collected at the central location with the EC system mounted at three levels above and within the forest canopy provide insight into aerodynamic transfer processes in the enclosed B2C rain forest biome. The sensible heat, CO₂, and water vapor flux measurements (although routinely calculated by the eddy correlation software) are not considered reliable and are disregarded in this analysis. The value of friction velocity, \( u_r \), is similarly unreliable at most measurement levels but may have some relevance at the base of the canopy where there are sustained winds due to the air handling systems. Results for \( u_r \) are included here for this reason.

Results for three 4-day periods when the EC system was installed at the central location at heights of 15 m (00:00 hours 26 June–24:00 hours 30 June 1998), 7.5 m (00:00 hours 4 June–24:00 hours 8 June 1998), and 3 m (00:00 hours 10 June–24:00 hours 14 June 1998) are shown in Fig. 6. Fig. 6a–c show the mean value of vertical wind speed \( (w) \), the variance of \( w \), and friction velocity at three heights. The most
obvious result is that there is very little turbulence at 7.5 and 15 m at the central location. However, near the base of the canopy (at 3 m), there is a fairly constant level of air turbulence. The higher and sustained turbulence at this level is almost certainly associated with the movement of air between the air handlers that are located below the canopy in the B2C rain forest biome. Nonetheless, Fig. 6d shows that \( \frac{\sigma_w}{u_*} \), the normalized standard deviation of \( w \), is between 4 and 6, suggesting very stable conditions even at 3 m height.

These results indicate that the transfer of energy and mass in the B2C rain forest is in the form of mass flow and molecular diffusion. Although the measurement of mean vertical wind speed provided by the EC system is prone to offset error and drift, Fig. 6a suggests that vertical mass flow plays some role in vertical transfer. Assuming these data are reliable, there is evidence of a tendency for the mean air flow (at the central location) in the B2C rain forest biome to be upwards at night and downwards during the day at both the bottom and above the canopy (at 3 and 15 m). It is intriguing that there is less evidence of a systematic daily cycle in vertical wind speed in the middle of the canopy (at 7.5 m). Perhaps this is because the EC system is in dense vegetation at this height, and the air prefers to flow through gaps elsewhere in the canopy.

3.2.2. Carbon dioxide and water vapor concentrations

Fig. 7 shows the concentration of CO\(_2\) measured by the EC system in the course of making the turbulence measurements reported in Section 3.2.1. Also shown are the equivalent CO\(_2\) concentrations measured at the ABRACOS Reserva Jaru site on four typical days. The apparent leveling-off of CO\(_2\) at high concentration is because the instrumentation could only monitor over
a predefined and limited range, and the concentration exceeded this range at night.

The most obvious result in Fig. 7 is that the CO$_2$ concentration inside the B2C is, on an average, approximately twice that of the earth’s atmosphere (compare the data from the ABRACOS Reserva Jaru site, Schimel et al., 1996; Culf et al., 1997). Further, the concentration of CO$_2$ undergoes a daily cycle of about a factor of two, much greater than that observed near the ground above the Amazon rain forest. Notwithstanding the fact that data for high concentrations are not available at night, the daily cycle of CO$_2$ concentration does not seem to vary much with the height of the EC system in the rain forest canopy. Decay of organic matter and soil microbial activities are the primary source of CO$_2$ release into the atmosphere of B2C, and these activities persist throughout the day.

In daylight hours, the plants in the B2C (in the rain forest and elsewhere) assimilate CO$_2$ rapidly, which causes the sharp decline in CO$_2$ concentration during the day. The CO$_2$ concentration in B2C is strongly related to the available solar radiation: on cloudy days, the minimum values of concentrations are higher than on (more common) sunny days. In general, the diurnal pattern of CO$_2$ concentration shown in Fig. 7 reflects the behavior of the entire BIOSPHERE-2 complex.

3.3. The water balance in the B2C rain forest

Overhead sprinklers are used to generate artificial ‘rain’ in the B2C rain forest. A few areas where sprinklers cannot be used are irrigated by drip irrigation. Typically, the sprinklers are turned on every 3–4 days, mainly on Tuesdays and Sundays. The amount of water applied during each application varies with season from the equivalent of about 7 mm in winter to about 11 mm in summer. Thus, the monthly precipitation in the B2C changes from around 30 mm per month in winter to about 50 mm per month in summer. Rainfall in the Amazon is much more variable and changes greatly with location and season. At the ABRACOS Reserva Jaru site, for instance, monthly rainfall may be less than 10 mm per month in the dry season, but at other times of the year, rainfall at this site (and at the other ABRACOS sites) can be several hundreds of millimeters.

There is a small amount of drainage from the soil in the B2C, but most of the applied water evaporates as transpiration from the plants. Gravimetric measurements of the moisture content of the surface soil layer were made at five locations in the B2C rain forest during this study. The results, which are shown in Fig. 8a, demonstrate that there were significant differences (up to 15%) in the water content in the surface soil layer between sample points. These may merely reflect local variations in the water-carrying capacity of the surface soils.

Two ‘Watermark’ soil water potential sensors were installed at depths of 0.05 and 0.85 m at one location in the B2C (see Fig. 1b for location). Restricted availability of logging systems meant these sensors were only monitored for a period of approximately 60 days.
in the Arizona winter and approximately 100 days in the Arizona summer. Figs. 8b and c show the measured water potential at 0.05 m depth for the winter and summer monitoring periods, respectively, while Fig. 8d and e show the measured water potential at 0.85 m depth for the winter and summer monitoring periods, respectively.

Fig. 8b and d demonstrate that there was little soil-moisture stress in the B2C soil at either sensor depth during the Arizona winter, although there is evidence of increasing soil-moisture stress towards the end of the observation period. Fig. 8c shows that, during the Arizona summer, near-surface soil-moisture stress begins to develop after each regular (3–4 days) application of rain in B2C, but there is always a rapid return to near-saturated soil after each application. In the case of the deep (0.85 m) sensor, the effect of the application of rain is less dramatic but still visible as fluctuations superimposed on a background soil-moisture stress typically between −200 and −400 kPa. On one occasion, in July, the soil water potential at 0.85 m reached −1000 kPa, but this dry period was short-lived and ended with the artificial rain on 3 August 1998. In general, it seems the imposed rainfall regime in B2C means the rain forest sees some limited soil-moisture stress at depth in summer; it does not experience prolonged periods of very strong soil-moisture stress. Presumably, this
is because the amount of moisture provided has been optimized to maintain a small but finite drainage from the soil column. The lack of strong or prolonged moisture stress in B2C rain forest soils emulates well the observed lack of moisture stress in Amazon rain forest soils (e.g., Gash et al., 1996; Nobre et al., 1996).

4. Discussion

This paper reports the results of a systematic year-long study of the micrometeorological environment in the enclosed B2C rain forest biome and provides a comparison with similar micrometeorological measurements made during the 4-year ABRACOS study at the three rain forest sites in the Amazon River basin. Although much can be done to control the meteorology and atmospheric composition in controlled environments such as the B2C rain forest biome, some factors are necessarily problematic. Clearly, the $S_i$ in a controlled environment depends not only on the opaqueness of the structure, but also on the geographic location of the facility and the ambient cloud cover outside the facility. A controlled environment located in Arizona cannot be expected to reproduce the small annual cycle in $S_i$ observed in tropical regions. However, this study shows that the often-cloudless skies in Arizona do significantly mitigate the effect of the glass and supporting structures on the radiation regime inside B2C during the Arizona summer, but they cannot be expected to do so during the Arizona winter. In general, the solar radiation climate of B2C is broadly equivalent to that at a mid-latitude site where there is consistent partial cloud cover. Recognizing and quantifying this equivalence in solar radiation regimes may be helpful in selecting the type of study that can be carried out in the B2C with most real-world relevance.

The extent to which energy capture by the glass and supporting structure influences the $T_a$, VP, and VPD above the canopy inside the B2C rain forest biome became obvious in the course of the present study. In some respects, it is beneficial that the buoyancy of the warmed air isolates it from the air in the underlying vegetation. This means that the meteorology in at least the lower portions of the B2C rain forest canopy better resembles that in the Amazon. Forced mixing of the air in the B2C rain forest biome would enhance the daily cycle of $T_a$, VP and VPD to which the rain forest vegetation is exposed and might thus worsen the overall comparability. Arguably, a better approach to enhance similarity with the real world would be to remove the energy near the roof of the B2C where it is captured by cooling the air.

In fact, the capture and storage of heat energy in the upper portions of the B2C rain forest biome is merely an example of a more general situation. A contained atmosphere above a soil–vegetation system will always emphasize the daily cycle in ambient properties of the near-surface air relative to that observed in nature. In the real world, the land surface has comparatively easy access to a deep layer of air that is well-mixed during the day. Moreover, the daily average properties of the contained atmosphere can easily differ from those of the real atmosphere. It seems that seeking greater comparability between enclosed and real-world conditions necessarily requires that air be removed from the enclosed environment near the roof because this is where the containment has the most effect.

This study shows that the primary atmospheric transfer processes in the B2C rain forest (a combination of mass flow and molecular diffusion) differ from those in the real world (a combination of turbulent transport and molecular diffusion). Removing this difference may well be an intractable problem because it is probably impossible to realistically reproduce the wind fields of a real forest in an enclosed environment. However, at the level of the cell or individual plant organism, the plant is only aware of adjacent ambient conditions, not the physical transfer processes that in part determine those conditions. With this in mind, it seems that future studies of plant behavior in the B2C (and in the rain forest biome in particular) need to put greater emphasis on monitoring the local, in-canopy meteorological environment. It is not sufficient merely to monitor meteorological conditions in the biome as a whole and to assume that the atmospheric transfer processes in the B2C and the real world are the same and that ambient conditions near the vegetation are therefore similar.

5. Concluding remarks

The basic purpose of this study was to compare the micrometeorological environment of the
BIOSPHERE-2 tropical rain forest biome with natural rain forest biomes. The results revealed some significant differences between the micrometeorology of two environments which are associated with structural aspects of the enclosure, and which will be used to guide future experimental research in this unique facility. Currently, B2C is installing a network of mass flow controllers for dispensing CO₂. This system is designed not only to eliminate the unnatural diurnal variation of CO₂ concentration, but also to maintain CO₂ concentration at prescribed, elevated levels, e.g., two to four times natural concentrations.

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References


