The Energy Balance of an Urban Canyon

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ABSTRACT

This study investigates the energy exchanges occurring within an urban canyon. It considers not only the energy balances of each of the canyon component surfaces (walls and floor), but also the balance of the canyon system and of the air volume contained therein. The results are based on measurements conducted in a specially instrumented canyon during a period of fine anticyclonic summer weather in Vancouver, B.C. The timing and magnitude of the energy regime of the individual canyon surfaces are shown to be very different from each other, each being strongly affected by the influence of the canyon geometry on the radiation exchanges. The diurnal course of the canyon system energy balance is relatively smooth and symmetric. By day the canyon system radiative surplus is mainly dissipated by turbulent transfer, and the remaining 25-30% is stored in the canyon materials. In contrast, the nocturnal radiative deficit is almost entirely balanced by the release of subsurface heat storage. Adective contributions to the air volume energy balance are shown to depend upon wind direction and speed, as well as the nature of the surrounding thermal environment.

1. Introduction

Although progress has been made, there is still no comprehensive study available concerning the surface energy balance of an urban area, [for a review of advances and problems in this field see Oke (1974)]. One of the most important reasons for this is undoubtedly the complex nature of the "surface". This leads to both conceptual and practical difficulties.

The most common approach is to treat the city from a holistic view point, that is, to ignore the exact nature of the surface (including both its spatial diversity and its vertical unevenness) and to treat it as an integrated system. Thus the energy and mass flows are assumed to relate to some datum height at about the level of the roofs. The datum roughly corresponds to the line of demarcation between the urban canopy layer and the urban boundary layer (Oke, 1976). This is the approach employed in most theoretical urban atmosphere models where the surface is assumed to be horizontal and homogeneous (e.g., Myrup, 1969; Atwater, 1972; Bornstein, 1972; McElroy, 1973; Barnum and Rao, 1975; Gutman and Torrance, 1975) and in measurements of areal fluxes over the city (e.g., Bowne and Ball, 1970; Yap and Oke, 1974).

The holistic view point treats the workings of the urban atmosphere below this datum as a "black box" in systems terminology. There are good reasons however to study the energy exchanges within the canopy layer. These include the practical value of understanding the energy loading of buildings and organisms (animal and vegetative), the importance of achieving a physical basis for the understanding of canopy layer microclimates, and the provision of realistic lower boundary conditions for urban boundary layer and urban air pollution dispersion modeling.

The present study was designed to investigate the energy input, partitioning and output of a characteristic urban canopy layer structure—an urban canyon (see Section 2 for definition). The methodology involves field measurement in an experimental canyon during anticyclonic summer weather, in a large mid-latitude city.

2. The urban canyon

There are probably no truly representative urban surfaces such as those identified as characteristic of rural and other horizontal natural terrain. However, there are some representative urban surface units whose basic form is repeated throughout the urban area. Such units consist of the more or less geometric combination of horizontal and vertical surfaces arising from the block-like arrangement of buildings and streets. These units recognize the essential three-dimensional nature of the urban canopy.

Here we recognize a basic urban surface unit to be the urban canyon. The canyon (Fig. 1a) consists of the walls and ground (usually street) between two adjacent buildings. The canyon air volume (Fig. 1b) is the air contained within this canyon structure and bounded at the top by an imaginary lid approximately at roof level. The top of this air volume, together with the
An experimental program was designed to measure all terms in (1) except \( Q_{hi} \), which was therefore obtained as a residual. Thus utilizing estimates of \([Q_A]\) and the values of \( Q_{hi} \) it was possible to gain some

![Diagram](image)

**Fig. 1.** Schematic depiction of (a) the urban/atmosphere interface, including an urban canyon and its canyon air volume (dashed); and (b) sensible heat exchanges into and out of the canyon air volume.

roof tops, forms the lower boundary for most of the urban boundary layer, at least in the center of most cities.

In this study we wish to ascertain both the partitioning of radiant energy by the active canyon surfaces (walls and floor) and the energy balance of the canyon air volume itself. The energy balance of the ith canyon surface is given by (see Appendix for a list of symbols)

\[
Q_i = Q_{hi} + Q_{ei} + Q_{gi} \tag{1}
\]

and the energy balance of the canyon air volume (in the case of a north-south oriented canyon and assuming no phase changes of water in the volume) is given by

\[
[Q_A] + \{H(Q_{hi} + Q_{hi}) + W(Q_{hi} - Q_{hi})\} = \int_V \left( \frac{\partial Q_i}{\partial t} + \nabla \cdot Q_i \right) dV. \tag{2}
\]

The left-hand side of (2) defines the net sensible heat input (or output) of the six sides of the canyon-air volume as a result of advection and turbulent transport (Fig. 1b). The right-hand side indicates that changes in the net energy status of the volume will be manifested as changes in sensible energy storage (air temperature changes) and/or net energy change due to volume radiative flux divergence.

![Diagram](image)

**Fig. 2.** The experimental urban canyon: (a) actual conditions (note the superstructure shadow on the east wall) and (b) schematic of instrument deployment, dimensions and coordinates.
understanding of the sensible heat transport in the
canyon air volume represented by the left-hand side of
(2). The interaction between the two terms on the
right-hand side of (2) has been dealt with by Nunez
and Oke (1976) for the nocturnal, light wind speed
case. Instrumental limitation does not yet allow the
same to be done for the daytime divergence of net
radiation.

3. Measurement

The experimental urban canyon (Fig. 2a) was located
in a mixed residential and light industrial zone, 6 km
southeast of the downtown core of Vancouver. The
canyon was situated between two food processing
plants, and was oriented with the along-canyon axis in
a north-south direction. The north end opened onto
railway tracks and the south end onto a major east-west
road.

The canyon walls were constructed of concrete and
were painted with several coats of flat white paint. The
floor consisted of a 30-50 mm layer of gravel and clay,
and there were a few patches of grass and low herb
plants along each wall. There were no windows and the
ventilation ports located on the roofs and at one end
of the canyon were not considered likely to produce
significant thermal effects. Superstructures on the roof
of the western building cast shadows on the east-wall
working area for a period in the late afternoon (Fig. 2a).
Data from this period were omitted from analysis. The
canyon was 79 m long, 7.54 m wide and the east and
west walls were 7.31 and 5.59 m in height, respectively.

Most of the experimental work was conducted at a
position 35 m from the north end of the canyon. At this
location an aluminum boom was fixed across the canyon
width at the height of the west wall. The boom formed
the trackway for a wheeled carriage which could
manually traverse the canyon. A vertical mast, at-
tached to the carriage, was instrumented with air
temperature and net radiation sensors mounted on eight
horizontal support arms at the heights shown in Fig. 2b.

Eight almost identical net pyrhiometers (Swissstco,
Model S1) were exposed in the following manner. The
highest and lowest net pyrhiometers were mounted in
the conventional horizontal position to measure a
vertical flux. The intervening six instruments were
placed with their receiving surfaces parallel to the
canyon walls. The polyethylene domes of the instru-
ments were purged by air passed through silica gel by
an aquarium pump. All the radiometers were calibrated
immediately prior to the experiments by the National
Radiation Laboratory of the Canadian Atmospheric
Environment Service. The corresponding eight air tem-
perature sensors were 24 AWG copper-constantan ther-
mosouples. Each was shielded against radiation, as-
pirated by a blower-fan at the rate of 3.5 m s⁻¹ and
referenced to an ice-point bath. [For a photograph of
the mast and sensor arrangement see Fig. 3 of Nunez
and Oke (1976).] As the mast crossed the canyon, it
was stopped so that measurements could be made at
five locations (corresponding to the floor flux plate
locations noted in Fig. 2b). This technique allowed cal-
culation of mean net radiation and air temperature
values for the four sides of the cross section (walls,
floor and top).

Subsurface heat flow into and out of the canyon
walls and floor was measured by heat flux plates.
Seventeen 13 mm diameter plates were embedded at a
depth of 5 mm in the walls and floor at positions cor-
responding to the radiometer and temperature sensor
locations (Fig. 2b). The plates were joined in series to
provide three signals corresponding to the mean flux
values of each of the canyon component surfaces.
Since the canyon floor was not impermeable, a miniatura
weighable lysimeter was installed in the center. The
design closely followed that of Pasquill (1950). The
lysimeter monolith was 0.1 m in diameter and 0.16 m
in depth. The unit was weighed on a beam balance,
and was estimated to provide a resolution of about
10 W m⁻² in hourly \( Q_E \) estimates, excluding observer
and sampling errors.

All signals were monitored on a data acquisition sys-
tem (Doric Scientific, Digitrend 210). Data were re-
corded at all positions once every 3 min during the day, and every 6 min between midnight and 0800 PST. All data were subsequently reduced to hourly averages.

The supplementary instrumentation required for the canyon advection experiment is outlined later.

4. Canyon energy balance

The canyon energy balance results are presented in this and the following section. In this section we consider the diurnal course of the energy balances of each of the canyon component surfaces, and then the equivalent fluxes at the canyon top. This assumes that the data from the boom-mast cross section are representative of the canyon and that advective influences are minimal. The following section analyzes the validity of these assumptions.

a. Surface energy balance of component surfaces.

Intensive observations were undertaken during the period 9–11 September 1973 inclusive. The weather was characterized by continually cloudless skies and weak airflow. Wind speeds in the canyon were < 2 m s⁻¹ by day and < 1 m s⁻¹ by night. There had been < 50 mm of rain in the preceding two months. The results for the three days were almost identical and were averaged.

The complete surface energy balances for each of the walls and the floor are given in Fig. 3. The floor balance was assumed to be given by (1), and substituting hourly average measurements of $Q_f^*$, $Q_{BI}$ and $Q_{AI}$, the value of $Q_{AI}$ was obtained as a residual. The walls were assumed to be impervious and hence their balance given by (1) with $Q_{BI}$ = 0, and $Q_{AI}$ obtained after substituting values of $Q_f^*$ and $Q_{AI}$. In most formulations of the urban energy balance it is normal to include an anthropogenic heat source term (e.g., Oke, 1974). This was not considered necessary in this case because any heat loss from the building interior would be sensed as a modification of $Q_{AI}$ for the walls, but would not introduce error in the measured surface energy balance.

The importance of canyon orientation on the energy balance is evident in Fig. 3. The north-south alignment results in maximum irradiance of the floor near solar noon, but on the west and east walls about 1.5 h before and after solar noon, respectively. Note also that the most active surface changes with time. In the early morning it is the west wall, at midday the floor and in the afternoon the east wall. Net radiant receipt, however, depends not only on illumination but also upon the angle of incidence, the surface albedo, emissivity and temperature. Prior measurement showed the mean albedos of the west wall, east wall and canyon floor were 0.62, 0.52 and 0.13, respectively. The low albedo of the floor combined with the small angle of incidence at midday produced the highest $Q^*$ absorption (> 400 W m⁻²). The higher albedos of the walls greatly reduce maximum absorption rates to ~ 200 W m⁻². The secondary $Q^*$ peaks on the walls are probably due to increased diffuse beam input caused by maximum irradiance of, and therefore maximum reflection from, the opposite wall. At night $Q^*$ is approximately the same for all surfaces. In absolute energy terms the floor of a north-south canyon is the most important exchange surface in the system.

During the day $Q_H$ is the dominant means of heat dissipation for all canyon surfaces. At midday $Q_H$ is 0.60$Q^*$ for the floor and 0.7–0.8$Q^*$ for the walls. Since $Q_{BI}$ is ~ 0.13$Q^*$ at this time, $Q_{AI}$ is ~ 0.25$Q_f^*$ for all surfaces.

At night turbulent transfer becomes of minor importance in the surface energy balances. On the floor $Q_{BI}$ remains slightly positive (i.e., weak evaporation, although the values may be within the limits of experimental error), but this is mirrored by negative $Q_{AI}$ which is also very small in magnitude. Similarly $Q_{AI}$ for each wall is very close to zero. Hence the nocturnal balance is approximately $Q_f^* = Q_{AI} \approx 50$ W m⁻².

b. Energy balance at the canyon top

Assuming that the energy involved in advection, canyon air temperature change and radiative flux divergence is small in comparison with the surface source terms in (2), then the sensible heat flux through the canyon top is

$$Q_H = (Q_{HI} + Q_{IH})(H/W) + Q_{HI};$$

(3)

similarly, the net radiation, subsurface and latent heat fluxes through the top are, respectively,

$$Q_f^* = (C_f^* + Q_f^*)H/W + Q_f^*,$$

$$Q_{AI} = (Q_{AI} + Q_{EI})H/W + Q_{AI},$$

$$Q_{BI} = Q_{BI}.$$

There is little reason to doubt the justification for the last two assumptions necessary to these formulations. The advective one is less evident, but probable limits will be suggested in Section 5.
The diurnal course of the energy fluxes through the canyon top in Fig. 4 is remarkably smooth considering the different phase relations of the individual surfaces in Fig. 3. The $Q_r$ curve is similar in many respects to that expected over simple horizontal terrain. In fact the absolute magnitude of the midday peak ($\sim 500$ W m$^{-2}$) and of the nocturnal "constant" loss ($\sim 70$ W m$^{-2}$) agrees almost exactly with unpublished measurements at 20 m over a downtown building at the same time, and favorably with the summer results of Yap and Oke (1974) at the same downtown site. The most significant difference is that the times when $Q^*$ passes through zero at the canyon top are 1 h later in the morning, and earlier in the evening. The general agreement between canyon and roof-top $Q^*$ raises the possibility that this may be a relatively conservative energy term across the city when viewed from aerial platforms.

By day $Q_{HI}$ is the dominant heat loss from the canyon. At midday $Q_{HI} = 0.64Q^*_r$, whereas $Q_{RI}$ is only $0.10Q^*_r$, giving a canyon $\beta$ value of $\sim 6.4$. This is considerably larger than the areal values of 1.2 in Montreal (Oke, et al., 1972) and 1.0 in Vancouver (Yap, 1973), and may be expected to represent close to an upper limit for $\beta$ in an urban area. Only areas totally devoid of vegetation might exceed this value. The subsurface term $Q_Q = 0.26Q^*_r$ at midday, and is therefore a significant energy sink. It should also be noted that $Q_Q$ peaks at solar noon and is therefore in phase with $Q_r$. Similar results were obtained by Yap (1973) for a roof site. It is normal for most rural sites to have $Q_Q$ reaching its maximum about 2 h before $Q^*$ (Sellers, 1965). No explanation is forwarded at this time.

At night $Q_{HI}$ and $Q_{RI}$ are both small and of the opposite sign so that they effectively cancel each other. Thus turbulent transfer was negligible at night under the weak airflow of this experiment. The absence of effective convective activity emphasizes the fact that radiative flux divergence must be the dominant cooling mechanism in the canyon air volume at night under these conditions as shown by Nunez and Oke (1976). The net radiative loss from the canyon is therefore balanced by drawing upon the reservoir of heat stored in the canyon materials by day.

5. Canyon advection

This section considers the heat transport into or out of the canyon air volume as a result of mean flow from the external environment. The transport may be accomplished in one or both of two ways. First, heat may be deposited or removed from the canyon as a result of horizontal flow through the ends of the canyon air volume. Second, the canyon geometry may induce its own vertical motions resulting in heat gain or loss through the top of the volume. Here we will consider these modes of transport for the two air flow possibilities illustrated in Fig. 5—flow along the canyon parallel to its walls (Fig. 5a), and at some angle of attack to the along-canyon axis (Fig. 5b).

**a. Flow parallel to canyon**

In the case of flow parallel to the canyon sides if we assume that there is no phase change of water and that energy storage change and radiative flux divergence are negligible in the canyon air volume, then we rewrite (2) as

$$
\rho c_p \left\{ \int_{A_1} u_1 \theta_1 dA_1 - \int_{A_1} u_3 \theta_3 dA_3 - \int_{A_3} u_3 \theta_3 dA_3 \right\} 
+ (Q_{HI} + Q_{H_0}) H L + Q_{HI} A_3 = 0,
$$

where the overbar denotes a time average. The first three integrals in (4) give the spatially averaged value of the instantaneous advective heat flux. The integrands can be expanded using the relations

$$
u_i = \bar{u}_i + \Delta \bar{u}_i, \quad \theta_i = \bar{\theta}_i + \Delta \bar{\theta}_i.
$$

Here the tilde denotes a space average over the area of a canyon air volume side. If it is assumed that the integral of all fluctuating variables is negligible, then
where the primes indicate instantaneous departures from the mean. Relations (6a) and (6b) decompose the instantaneous velocity and temperature fields into a mean and a fluctuating part; (6c) implies a loss of mean wind velocity along L; and (6d) describes the mean temperature at the canyon top in terms of that on the upwind side. Substituting (6a)–(6d) in (5), and neglecting divergence in the horizontal turbulent transport term (i.e., \( \overline{u'v'} \approx 0 \)) gives

\[
\rho C_p \left( (\pm \Delta \xi_1 (\overline{U_1 - \Delta U_1}) + \Delta \xi_2 \Delta U_1) A_1 - (\overline{U_1 \Delta \xi_2 + \overline{u'v'}}) A_3 \right) + (Q_{H_2} + Q_{H_3}) HL + Q_{H_4} A_3 = 0. \tag{7}
\]

With very light winds the canyon air volume source terms in (7) will be balanced by the turbulent flux \( \rho C_p \overline{u'v'} \) through the volume top, and the remaining terms will almost vanish. This is likely to have been the case during the energy balance experiment period described in Section 4. However, to check the magnitude of these other terms and to study their behavior over a slightly expanded range of wind speeds, some simple experiments were conducted.

Two masts were erected in the canyon to measure wind speed and air temperature changes along the canyon axis. They were located at canyon mid-width, separated by a distance of 28 m, with the southernmost mast 40 m from the south end. The instruments were mounted on cross-arms at 1.8 and 3.7 m above the canyon floor. Air temperatures were measured with 26 AWG copper-constantan thermocouple difference systems. The sensors were aspirated and shielded against radiation. Wind speeds were measured by sensitive cup anemometers (C. W. Thornthwaite Assoc.), and wind direction was monitored by a Gill wind vane (R. M. Young Co.) mounted between the two masts. Observations were made every 2 min during four cloudless days in July 1973. The data were reduced to hourly averages.

First we will investigate the term in (7) which represents the heat transport due to the mean wind in

![Fig. 7. Relation between absolute advective transport due to the mean horizontal wind in combination with the mean horizontal temperature gradient \( \left( \rho C_p \overline{u'v'} (\overline{U_1 - \Delta U_1}) A_1 / A_3 \right) \) and the canyon wind speed \( \overline{U_1} \). Data from the period 10–13 July 1973. Line is an eye-fit.](image)
combination with the mean horizontal temperature gradient \([i.e., \pm \rho c_p \Delta \Theta_1 (U_1 - U_1')]\). Fig. 6 shows the experimental results of this term expressed as an equivalent flux through the canyon top (i.e., comparable to the fluxes given in Section 4b). The sign of the advective transport is clearly related to the wind direction. Winds from the south (highway end) produce warming, and from the north, cooling, of the canyon air volume. This suggests that the extra-canyon environment is warmer at the south end. This is confirmed by horizontal radiative flux divergence measurements made at night in the same canyon (Nunez and Oke, 1976). Given similarity of the weather conditions on the four days the absolute magnitude of the advective transport is seen to be related to the canyon wind speed (Fig. 7). The eye-fit to these data indicates that on cloudless summer days with winds of 2 m s\(^{-1}\) this term would contribute an advective transport of \(\sim 70\) W m\(^{-2}\); at 1 m s\(^{-1}\) this value would drop to about 15 W m\(^{-2}\). There is the likelihood that this term has an upper limit conditioned by the fact that increased wind speeds will destroy the temperature differential \((\Delta \Theta_1)\). The second and third terms in (7) \([i.e., \rho c_p (\Theta_1 \Delta U_1 A_1 - \Delta \Theta_1 A_4)]\) arise out of the frictional retardation of air flow along the canyon surfaces. Deceleration of the horizontal velocity must result in uplift (Fig. 5a). Since the two are related by the equation of continuity for incompressible flow

\[
\bar{U}_3 = \Delta \bar{U}_1 A_1 / A_3. \tag{8}
\]

The vertical flow \((\bar{U}_3)\) will transport energy out of the canyon air volume. Substituting (8) in the expression at the beginning of this paragraph gives the advective term

\[
\rho c_p A_1 \Delta \bar{U}_1 (\bar{\Theta}_1 - \bar{\Theta}_3) \tag{9}
\]

such that if \(\bar{\Theta}_1 > \bar{\Theta}_3\) the air volume will be warmed, and if \(\bar{\Theta}_1 < \bar{\Theta}_3\) it will be cooled by this vertical transport. The frictional loss \((\Delta \bar{U}_1)\) is a function of the horizontal wind velocity, as shown in Fig. 8. Unfortunately \(\bar{\Theta}_1\) and \(\bar{\Theta}_3\) were not measured simultaneously in this study, but using the September results (Section 4) we can arrive at both maximum and reasonably typical estimates. Maximum values of \((\bar{\Theta}_1 - \bar{\Theta}_3)\) were 0.2°C; if this were used in (9) with the maximum \(\Delta \bar{U}_1\) value of 2.0 m s\(^{-1}\) from Fig. 8 (corresponding to \(U_1 = 4.75\) m s\(^{-1}\), and \(U_3 = 0.40\) m s\(^{-1}\)) it would give a maximum equivalent advective flux through the canyon top of \(\sim 95\) W m\(^{-2}\). This is certainly an overestimate since it is not likely that the maximum \((\bar{\Theta}_1 - \bar{\Theta}_3)\) value would coincide with such relatively strong winds. More typical values \(e.g., \Delta \bar{U}_1 = 1.0\) m s\(^{-1}\), \(U_1 = 2.6\) m s\(^{-1}\), \(U_3 = 0.19\) m s\(^{-1}\), \((\bar{\Theta}_1 - \bar{\Theta}_3) = 0.1\)°C] reduce this figure to \(\sim 25\) W m\(^{-2}\).

With weak along-canyon flow such as that encountered in the September experiments we may therefore reasonably anticipate total advective transport to be less than 100 W m\(^{-2}\). 

b. Flow at an angle to the canyon axis

With flow perpendicular to the canyon axis a vortex circulation develops, and at the other angles of attack some form of "cork-screw" type action is to be anticipated (Fig. 5b). The vortex circulation was first described and measured by Albrecht (1933), verified by carbon monoxide concentration measurements by Georgii et al. (1967), and recently modeled by Nicholson (1975). In this study this circulation pattern was observed both by visual tracers and from measurements of vertical wind speed from Gill propeller anemometers (R. M. Young Co.) placed at three locations across the canyon top (Fig. 9). The results indicate a downdraft near the east wall and updrafts near the west wall and center. The asymmetry may be due to the uneven wall heights (Fig. 2b), and to uplift in the canyon air volume arising from frictional retardation of the along-canyon component of the wind.

In this type of vortex situation the mean vertical flow

\[\text{Fig. 8. Relation between frictional loss of horizontal velocity (} \Delta \bar{U}_1 \text{) due to traveling 28 m along the canyon, and the canyon velocity (} \bar{U}_1 \text{). Data from the period 10–13 July 1973.}\]
may be important in transporting heat to or from the
canyon air volume and providing substantial interaction
with the overlying urban boundary layer. The
sensible heat transport through the canyon top is then
given by

\[ Q_{HI} = \int_{A_1} \left( \overline{u} \Delta \overline{\theta} \right) dA_3 / A_3 \]

\[ = \int_{A_3} \left( \overline{\Delta \overline{u} \overline{\theta}} + \overline{u \Delta \overline{\theta}} + \overline{u \overline{\theta}} \right) dA_3 / A_3. \] (10)

The first term in the integrand is the flux associated
with the mean flow, whereas the last two are turbulent
fluctuations in the time and space scales. Although we
neglected the term \( \Delta \overline{u} \Delta \overline{\theta} \) in (4), it may be significant
in this case because \( U_0 \) is expected to vary over \( A_3 \)
(Fig. 9). Consequently the total flux in (10) must be
the sum of these three quantities averaged over \( A_3 \).

Unfortunately the measurements of the present study
are insufficient to investigate the magnitude and sign
of the advective transport given by (10). This case is the
most general canyon flow situation and warrants re-
search. It is especially important to investigate the heat
exchange between the roof-tops and the canyon. In the
early morning and late afternoon the canyon is largely
in shadow but the roof-tops are in receipt of solar
radiation. At night the greater sky view factor of the
roof-tops allows them to radiate more effectively than
the canyons. These heating and cooling differences
provide ample possibility for roof-canyon advective
interaction.

6. Summary

This study has investigated the energy exchanges oc-
curring in an urban canyon in mid-latitudes in fine
summer weather (light winds and cloudless skies). The
timing and magnitude of the surface energy balances
of the canyon walls and floor are strongly conditioned
by the influence of the canyon geometry and orienta-
tion on the radiation exchanges. In the case of the
north-south canyon used this results in the floor being
the most active energy site. For all surfaces the day-
time radiant surplus is preferentially channeled into
sensible heat transfer via turbulence, but subsurface
heat storage is substantial. Computation of the energy
balance for the complete canyon system (viewed as an
equivalent flux through the canyon top) shows that
approximately 60% of the midday radiant surplus is
lost as sensible heat to the air, and approximately 30%
is stored in the canyon materials. The remaining 10%
is consumed by evaporation from the canyon floor.
At night with weak winds the turbulent activity be-
comes negligible and the canyon balance consists of the
net radiant deficit being offset by the release of energy
stored in the canyon materials. Preliminary studies of
the advective transports indicate that with airflow
parallel to the canyon sides the advective contribution
depends upon the wind speed, as well as the energy
availability exterior to the canyon system. With 2 m s\(^{-1}\)
canyon wind speeds the maximum advective transport
is estimated to be \( \approx 170 \) W m\(^{-2}\), whereas at 1 m s\(^{-1}\) it
is \( <50 \) W m\(^{-2}\). With airflow at an angle to the canyon
axis it appears as if transport by the mean flow may be
important, but this could not be evaluated here.

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APPENDIX

List of Symbols

\[ A_1 \] area of the canyon cross section [W\( \times \)H (m\(^3\)])
\[ A_3 \] area of the canyon air volume top [W\( \times \)L (m\(^3\)])
\[ H \] canyon height (m)
\[ L \] nominal canyon length (m)
\[ Q^* \] net all-wave radiation flux (W m\(^{-2}\))
\[ Q_A \] net advected heat due to horizontal transport
\[ (J s^{-1}) \]
\[ Q_{sh} \] latent heat flux (W m\(^{-2}\))
\[ Q_o \] subsurface heat flux (W m\(^{-2}\))
\[ Q_H \] sensible heat flux to the air (W m\(^{-2}\))
\[ U \] time-averaged wind speed (m s\(^{-1}\))
\[ V \] canyon air volume [H\( \times \)L\( \times \)W (m\(^3\)])
\[ W \] canyon width (m)
\[ c_p \] specific heat of air at constant pressure (J kg\(^{-1}\)
\[ K^{-1})\]
\[ t \] time (s)
\[ u \] instantaneous wind speed at a location (m s\(^{-1}\))
\[ y \] distance across canyon (m)
\[ z \] height above canyon floor (m)
\[ \beta \] Bowen's ratio [= \( Q_H/Q_{sh} \) (dimensionless)]
\[ \theta \] time-averaged air temperature (K)
\[ \rho \] instantaneous air temperature at a location (K)
\[ \rho \] air density (kg m\(^{-2}\))

Subscripts
\[ e, w \] canyon east and west walls, respectively
\[ f, t \] canyon floor and top, respectively
\[ 1, 2, 3 \] faces of the upwind, downwind and top of the
canyon air volume

Brackets—square brackets indicate a volumetric average.

REFERENCES

Albrecht, F., 1933: Untersuchungen der vertikalen Luftzirkula-


