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MEASUREMENTS OF SURFACE-ATMOSPHERE ENERGY BALANCE COMPONENTS IN CENTRAL BARCELONA (SPAIN) DURING SUMMER

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ABSTRACT

The aim of the study was to conduct observations of the surface energy balance in Barcelona and relate the results to features of the climate and surface morphology. The eddy correlation approach was used to measure directly the turbulent sensible and latent heat fluxes. Measurements were conducted on the roof of the University of Barcelona central building, in June of 2001. The site is close to the urban heat island core. Results show that the convective sensible heat flux (Q_H) dominates (34% of net radiation) over the heat used for evaporation (9%) in view of the scarcity of green areas. The largest proportion of energy went for storage in the building fabric (56%).

Key words: urban energy balance, urban heat island, Barcelona.

RESUMEN

Se llevaron a cabo medidas del balance de energía superficial en la ciudad de Barcelona, empleando el método de correlación turbulenta para medir directamente los flujos convectivos de calor sensible y latente. Las medidas se realizaron en la azotea del edificio

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histórico de la Universidad de Barcelona, en el centro urbano, cerca del núcleo de la isla de calor de la ciudad (junio de 2001). Los resultados muestran que el flujo de calor sensible (Q_H) fue dominante (34% de la radiación neta) respecto al calor latente (9%), debido a la escasez de áreas verdes. La proporción más grande de energía se almacenó en los materiales de los edificios (56%).

Palabras clave: balance de energía urbano, isla de calor, Barcelona.

I. INTRODUCTION

It is well established that substitution of rural surfaces by urban elements induces changes of the local climate. Alteration of the land surfaces by urbanization generates distinct urban climates. Such features as the heat island, precipitation enhancement and air pollution are well documented (Oke, 1979; Landsberg, 1981).

A further step in the study of urban climates is the knowledge of how the net radiation falling on the urban fabric is partitioned. The energy balance of a city can be expressed as

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \ (\mathrm{Wm^{-2}})$$

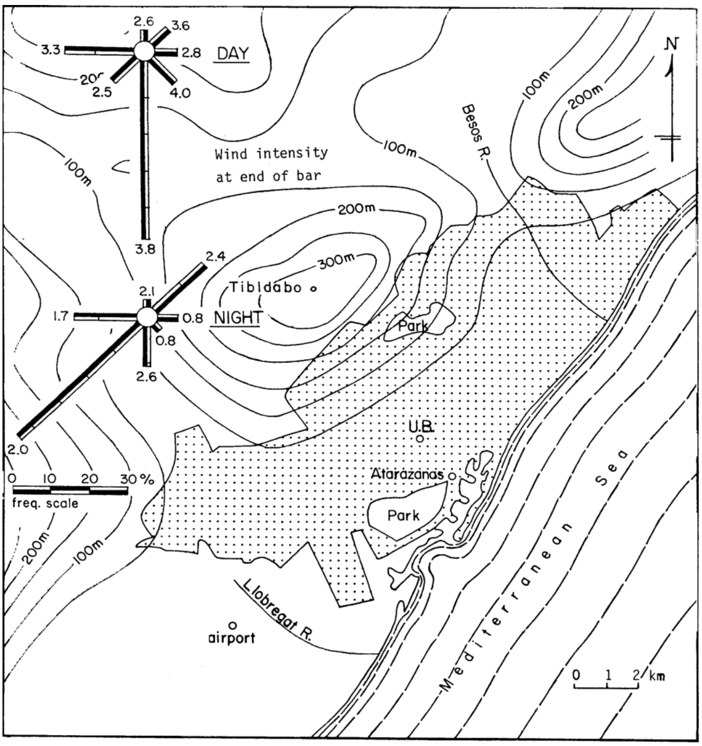
where Q^* is the net all-wave radiation, Q_F is the anthropogenic heat flux, Q_H is the sensible heat flux, Q_E is the latent heat flux, ΔQ_S is the net storage heat flux and ΔQ_A is the net horizontal advection. In this study the storage heat flux is determined as the energy balance residual from direct observation of net all-wave radiation Q^*, sensible Q_H and latent heat Q_E fluxes. Consequently, all measurement errors of the other energy balance fluxes are accumulated in this term. Other errors introduced in the residual ΔQs are horizontal advection ΔQ_A and anthropogenic heat flux Q_F that are not measured. Q_F sources in the vicinity of the observation site are mainly from vehicle traffic on major roads. The effect of sea breeze (3 to 4 m/s) advection although of some relevance in the afternoon was not evaluated. There is not objective evidence on the magnitude of the errors, but it is reasonable to consider that the instrumental errors, the influence of the horizontal advection and the anthropogenic heat flux can be as large as the storage heat flux.

Most studies on energy partitioning in urban areas have been undertaken in suburban areas in North America where the dominant land-use in terms of areal extent is characterized by detached houses with vegetation surrounding the building structure. As suggested by Grimmond and Oke (1995), to fully understand the processes that take place in urban areas and develop numerical models, it is important to have direct flux measurements from a greater range of cities. Being the second largest urban area (478 km^2) of Spain with an old historic core, it was considered of interest to conduct an energy balance field experiment in Barcelona in order to continue studies of energy balance at intensely developed sites, with the purpose of getting a better understanding of the role of urban morphology in the development of the urban heat island. Another aim of the study was to compare results with those obtained in other cities with similar urban morphology (e.g. central Mexico City), or contrasting geographical location. With exceptions, most studies of energy partitioning have been conducted in suburban areas of North America measuring both latent and heat fluxes. Surface energy balance measurements have been also undertaken in the cities of Marseille, France (Grimmond et al, 2002; Lagouarde et al, 2002) and Lódz, Poland (Offerle et al, 2002). In this paper the energy balance of a downtown area in a coastal city on the Mediterranean Sea is presented.

II. GEOGRAPHICAL LOCATION AND CLIMATE

The city of Barcelona lies on the Mediterranean coastal plain of Spain not far from the border with France (Fig. 1). The city is located on a strip (~ 8 km wide) of coastal plain between the mountain ranges (with altitudes of 250-500 m) and the coastline. Two river valleys delimit the main urban area: the Llobregat river to the south-west and the Besos to the north-east (Fig. 1). Heating of the slopes of mountain ranges induces during the day upslope winds that are reinforced by the sea breeze circulation with peak speeds of 7-8 m/s in the afternoon (Soriano et al, 1998). This local wind blowing from the south sector prevailed during the experiment with a frequency of 49%. The second most frequent wind blew from the west with a frequency of 18%. Some physical properties of the urban morphology of these two sectors around the site are examined in section III.

Figure 1
SITE LOCATION (UB) AND WIND ROSES (DAY AND NIGHT) DURING EXPERIMENT IN JUNE 2001 IN BARCELONA



The population of Barcelona is around 1.6 millions (3 millions in metropolitan area). The city has a typical temperate Mediterranean climate with dry summers and a rainy period in autumn (600 mm/yr). Summer temperatures may on occasions rise to near 30-35 °C in July and August. During the measurement period the synoptic conditions were controlled by the position of the Azores anticyclone, except on June 17th when a frontal passage produced increasing cloudiness and light rain in the afternoon.

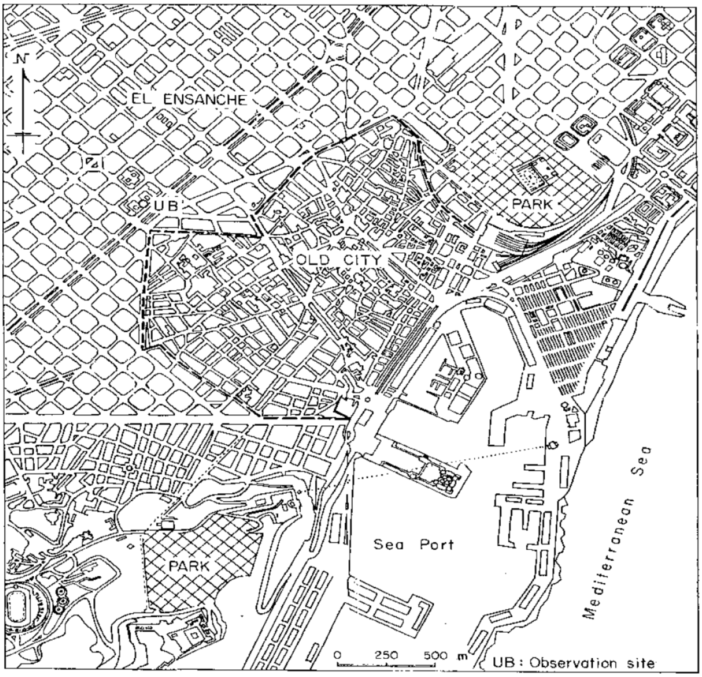
III. THE SITE

The observation site is located on the southern edge of the central section of the city known as the Ensanche, a late nineteenth century urban development characterized by wide straight roads lined with two or more rows of trees. The SE sector is occupied by the medieval city with no space between three-to-four story massive constructions and almost no greenery on the narrow streets. Bordering to the SE of the old city is the industrial, commercial seaport (Fig. 2). Most buildings in the Ensanche have flat roofs and are very uniform in height (6 to 8 stories or about 15-20 m high) and closely packed. The characteristics of the surface morphology of the site were assessed by field surveys. A detailed survey was conducted for an area with a radius of 0.5 km in the directions of the most frequent wind during the day time (when Q*>0) e.g. the southern and the western sectors, as mentioned above with frequencies of 49 % and 18%, respectively. Applying the procedure of Schmid (1997) for footprint evaluation, it was found that these two sectors represented 2/3 of the source areas of the turbulent fluxes reaching the instruments listed in Table 1. The surface morphology in the other directions is similar to those described for the west and south sectors (see Figure

Table 1
ENERGY BALANCE INSTRUMENTS USED IN BARCELONA

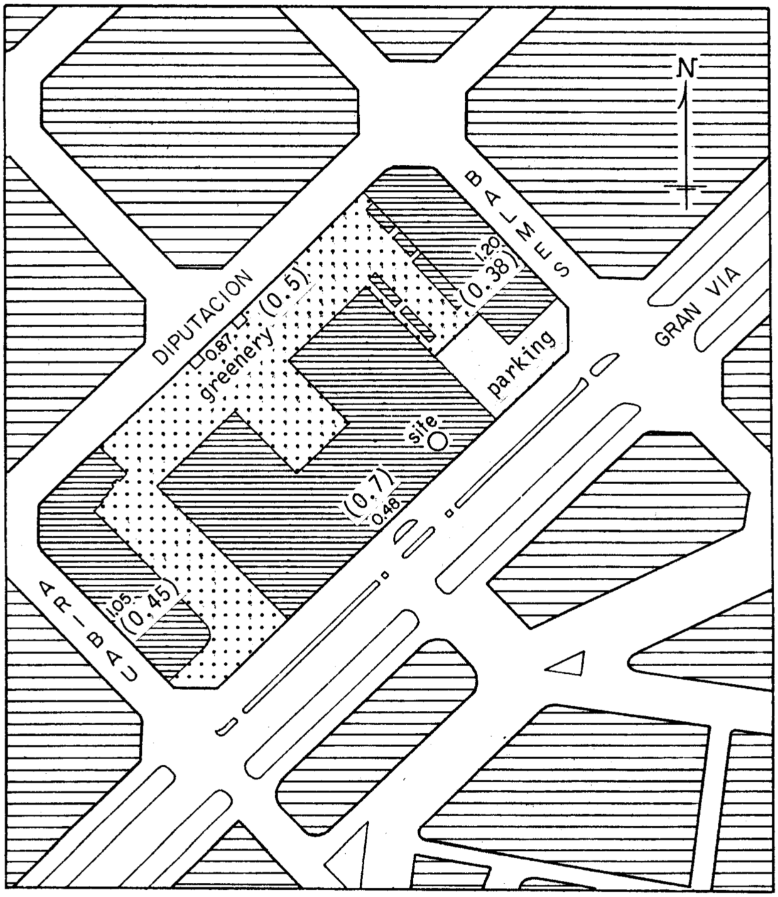
Variable	Instrument	Height above roof	
V,horizontal wind speed	Anemometer RM Young	9.0 m	m/s
Wind direction	Wind vane RM Young	9.0 m	Degrees (azimuth)
K^{-}, global radiation	Pyranometer Licor	3.2 m	Wm^{-2}
Q*, net all-wave rad.	Net radiometer Campbell	8.0 m	Wm^{-2}
Qh, sensible heat flux	Sonic anemometer Campbell	8.0 m	Wm^{-2}
Qe, latent heat flux	Krypton hygrometer Campbell	8.0 m	Wm^{-2}
T, air temperature	Thermometer Vaissala	3.8 m	°C
HR, relative humidity.	Hygrometer Vaissala	3.8 m	%
W, vertical wind speed	Sonic anemometer	9.0 m	m/s

Figure 2
MAP OF CENTRAL BARCELONA SHOWING LOCATION OF OBSERVATION SITE



2). The buildings surrounding the site are mixed commercial/residential and typical of much of the city; they are built of stone and brick with concrete or tile roofs (in the old city). Roads are paved with concrete or asphalt. As shown by Oke (1981) the magnitude of urban-rural temperature difference ΔT_{u-r} is closely correlated with the geometry of the canyon. For an urban canyon consisting of a street of width W and bounded by buildings of height H, the ratio H/W is inversely related to the rate of cooling. In other words, for a relatively constant street width the taller the buildings lining the street (or the deeper the canyon) the lower the cooling rate. In order to give an idea of the canyon geometry, H/W values were estimated around the University of Barcelona building (Figure 3), where the data were collected. The building faces a broad avenue and therefore a corresponding low H/W value, while the streets on the back (Diputación Street) and sides (Aribau and Balmes streets) of the building, being narrower, show higher values of H/W. The value of H/W (0.87) for the Diputación street (measured at the street corner) is probably too high to represent the whole canyon since a broad green area with some mature trees separates the back of the university building from the street and where the H/W value is reduced to 0.4 (see Figure 3). In a radius of 500 m, building heights vary in the sectors of the main source areas (the most frequent wind directions, being south and west sectors). In the south sector (the sea breeze direction) building heights range between 15 ± 2.5 m (5 to 6 stories) while in the west sector (the second most frequent daytime wind direction) building heights are between 22.4 ± 2.8 m (7 to 9 stories high). These values indicate that there is considerable shade by day.

Figure 3
VIEW FACTOR MEAN VALUES (MEAN BUILDING HIGH/MEAN STREET WIDTH, H/W) AROUND THE SITE OF THE UNIVERSITY OF BARCELONA



The ratios of the three to the two-dimensional surface area (or complete area to the plan or bird's eye view) are 1.41 and 1.59 for the south and west sectors, respectively. These active surface ratios are somewhat lower than the one (1.75) found by Oke et al (1995) at the School of Mines (SM) in Central Mexico City. In the western source area, vegetation cover is limited to rows of mature deciduous trees on the streets of the Ensanche. In this sector, the area of walls is larger than the roof areas and the ratio of walls/roofs being 1.59. In contrast, green areas in the south source sector (the sea breeze sector) are rather scarce. This is the area occupied mostly by the old medieval town where the ratio of area covered by roofs to that of walls is 1.8 and the ground occupied by alleys is reduced to a minimum.

The visual area covered by the net radiometer was estimated considering a view angle of 85° around the vertical in all directions, sufficient to capture 99% of the upwelling radiation contributions (Schmid, 1997). The radius of the visual area is (R):

$$R = 11.43\,(h\text{-}hd) = 240\text{ m} \qquad 1)$$

where h is the height of sensor and hd is the displacement height evaluated as:

$$hd = (\Sigma\ Aihi) / (\Sigma\ Ai)$$

where Ai is the horizontal building area and hi is the height of building (m)

An iterative procedure was applied starting with i= 1 km to finally obtain a lower visual radius value for the net radiometer of 240 m.

This radius was compared with the source area of the sonic anemometer and krypton hygrometer, estimated by the procedure proposed by Schmid (1997). For the net radiometer the radius is approximately 294 m, while for the other sensor the radii are between 300 to 600 m, depending on the horizontal wind speed. However, the land uses monitored for both type of sensors are almost the same: 80% of the area is covered by buildings (mostly commercial-residential), 10% by streets and 10% by parks.

The increase in effective surface area due to the rugosity of the urban interface is greater in the old center of Mexico City due to a higher mean height of the buildings. Figure 4 shows the mean cooling rates that prevailed at the Barcelona site during the experiment and those observed at the downtown Mexico City site during the 1-7 December experiment. Notwithstanding the relatively low H/W values of street canyons in Barcelona, mean cooling rates during the experiment were relatively low as compared with those observed at the School of Mines (SM) in Central Mexico City in winter. This contrast in cooling rates is likely to be due to the considerably higher humidity conditions (associated with a higher local greenhouse effect) that prevailed in Barcelona (q= 10.9 g/kg) (Table 2) than those observed (6.8 g/kg) in the SM experiment thus reducing the rate of cooling.

Table 2

HUMIDITY CONDITIONS IN BARCELONA AND CENTRAL MEXICO CITY DURING THE ENERGY BALANCE EXPERIMENTS

	Relative humidity (%)		**Specific humidity (gr/kg)**	
	Barcelona	**School of Mines**	**Barcelona**	**School of Mines**
All cases	61	51	10.9	6.8
Day	52	42	9.6	6.6
Night	79	62	11.9	7.0

IV. METHODOLOGY

The eddy covariance approach was used to measure directly the turbulent sensible and latent heat fluxes with the instruments mentioned in Table 1 in the constant flux layer of the urban boundary layer (Oke et al, 1989). The objective was to represent the fluxes for an integrated surface type representative of the urban texture (Oke, 1982). Given the difficulty

Table 3
MEAN STORAGE FLUX INTEGRATED OVER 24 H (MJM^{-2}), DURING THE BARCELONA CAMPAIGN

	Q*	Q_H	Q_E	ΔQ_S
Day (Q* > 0)	19.1	6.6	1.0	11.5
Night (Q* < 0)	-2.9	0.6	0.4	-3.9
Day + Night	16.2	7.2	1.4	7.6

Table 4
SUMMARY OF MEAN ENERGY BALANCE FLUXES FOR CLEAR SKY CONDITIONS, WHEN Q>0, IN BARCELONA AND OTHER CITIES*

	DL (hs)	Obs. period	Q_H/Q*	Q_E/Q*	ΔQ_S/Q*	Q_H/Q_E
Barcelona (downtown)	13	16, 19-21 June 2001	0.34	0.09	0.56	7.1
School of Mines, Mex. City (downtown)	12	1-7 Dec. 1993	0.38	0.04	0.58	9.9
+ +Vancouver (industrial)	13	11-26 August 1992	0.42	0.10	0.48	4.4
+ +Los Angeles (residential)	12	July 4-Aug 11 1993	0.49	0.22	0.29	2.2
++Chicago (residential)	13	June 14-Aug 10, 1995	0.46	0.37	0.17	1.2

+Data from Oke et al, 1999.
++Data from Oke et al, 1995.

Figure 4
COOLING RATES (Y-AXIS IN CUMULATIVE °C) FOR BARCELONA (16, 19-21 JUNE/01) AND SCHOOL OF MINES (1-7 DECEMBER 1993), AS FUNCTION OF LOCAL TIME (X-AXIS)

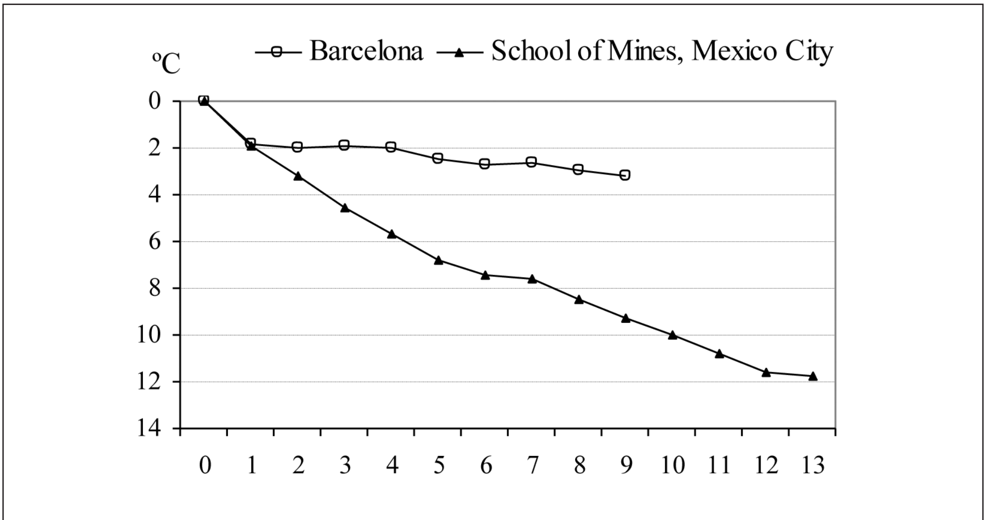


Figure 5
ENERGY BALANCE DURING CLOUDLESS DAYS (MEAN OF HOURLY DATA FOR 16, 19-21 JUNE 2001) IN BARCELONA, AS FUNCTION OF LOCAL TIME

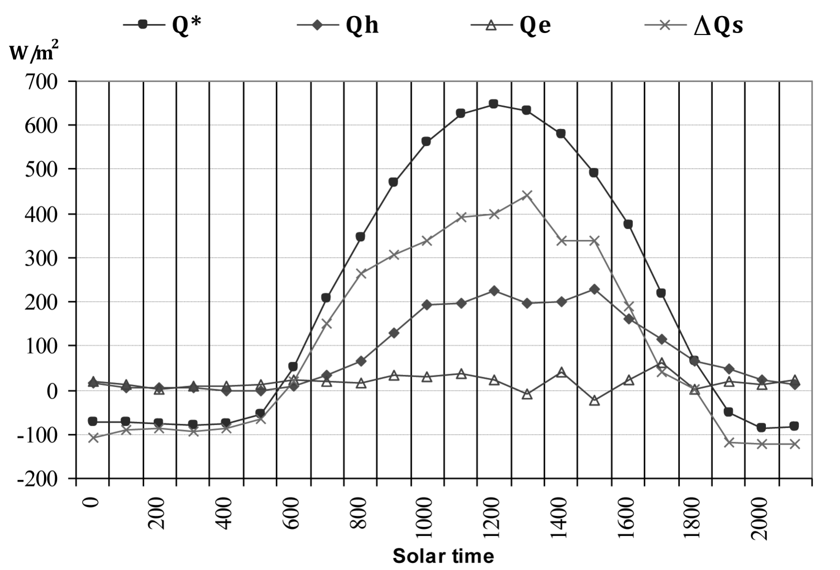


Fig. 5 Average fluxes at the University of Barcelona site for 16,19-21 June 2001.

of measuring ΔQs, it was estimated as the residual in the energy balance. Moreover, neither anthropogenic heat flux nor the advection term were determined in this study. ΔQ_F values should not be expected to exceed those estimated by Oke (1988) since summer time building cooling is not dominant in Barcelona. Horizontal advection is difficult to estimate. The site is influenced by land/sea breeze circulation. In a study conducted in a coastal site (Vancouver), Steyn (1985) concluded that advection could be neglected. However, it is possible that in the Barcelona experiment advection effect by the vigorous (3 to 4 m/s) sea breeze is likely to have been of relevance in the energy balance equation. Consequently, ΔQs magnitudes in Tables 3 and 4 and figure 5 should be taken with caution.

V. INSTRUMENTATION

The instruments were mounted on a 9 m mast on the roof of the University of Barcelona, a three story old building, 37 m over the street. The site is close to the observed maximum of the nocturnal canopy layer heat island which in the mean monthly average is 2.5°C for the month of June (Moreno, 1994). Instruments were calibrated in the instrumentation department of the Center of Atmospheric Sciences (UNAM). They were fixed at the various heights above the roof as indicated in Table 1. Those heights are similar to those of the Marseille experiment (Grimmond et al, 2002); however, in Marseille, two levels (43.9 m and 34.6 m) were used, depending on wind speed, rather than the fixed 37 m height in Barcelona.

Table 5
DAY/NIGHT METEOROLOGICAL COMPARISONS DURING THE BARCELONA EXPERIMENT

	Horizontal wind (m/s)	Wind vertical component (m/s)	Specific humidity (g/kg)	Relative Humidity	T ºC
All cases	2.8	0.13	10.9	61	23.7
Day (Q*>0)	3.4	0.17	9.6	52	24.2
Night	1.6	0.05	11.9	79	20.9

Table 6
FUNDAMENTAL CHARACTERISTICS OF THE ROUGHNESS SUBLAYER DURING THE EXPERIMENT

	Unstable atmos.	Neutral atmos.	Stable atmos.
Q_H, Turbulent sensible heat flux (Wm^{-2})	Q_H >10 Wm^{-2}	$0 \leq Q_H \leq 10$ Wm^{-2}	$Q_H < 0$
U* friction velocity (m/s)	0.7	0.1	0.05
L, Monin-Obukov length (m)	-267	-24	10
Zo Roughness height (m)	2.8	0.7	0.3
H, surface layer height (m)	93	30	15
Number of cases	144	52	45

VI. WEATHER CONDITIONS

6.1. Temperature, humidity and wind

Table 5 shows average temperature, humidity and wind conditions that prevailed during the experiment (16, 19, 20 and 21 June 2001). Temperature contrasts between day and night were small while the speed of the wind decreased to about half the daytime value. As expected, the nighttime relative humidity increased with the lower nocturnal temperatures.

Prevailing surface winds were the sea breeze from the south and the land breeze from the SW (Fig. 1).

6.2. Surface layer characteristics

Table 6 shows values of basic properties of the surface layer, for large and positive (>10 Wm^{-2}), negative (< 0) and near-zero (0 to 10 Wm^{-2}) values of Q_H. The values of friction velocity and Monin-Obukov length were estimated from the covariance of vertical and horizontal wind for the whole data set for each condition of Q_H (negative, close to 0 or higher than 10 Wm^{-2}).

Considering that negative values of the Monin-Obukov length indicate the height at which flotation forces are balanced by turbulent impulse, the results of Table 6 show a clear congruity among the variables: positive values of Q_H are reflected in higher values of the friction velocity, and roughness sublayer depth. The different values of roughness height for different stability conditions can be associated with the footprint related to each prevailing wind direction for each stability condition.

VII. RESULTS

Prevailing weather was so uniform (cloudless skies except for one day) that a simple ensemble mean day (consisting of mean of hourly data for 16, 19-21 June 2001) gives a representative picture of energy partitioning between terms in the energy balance for cloudless days (Fig. 5). Only average fluxes for the measurement period were considered in this paper.

The daytime period is characterized by higher peak values of net radiation (around 640 Wm^{-2}) in a practically smog-free atmosphere as compared with those observed in a tropical region like Mexico City (440 Wm^{-2}) where the pollution layer attenuates short wave radiation.

While during the night the net radiation loss was large (around –90 Wm-2) the storage release supplies energy equivalent to a somewhat larger amount of the net radiation.

Table 3 shows the mean storage flux integrated over 24 h (MJm^{-2}), during the Barcelona campaign, while table 4 summarizes energy balance flux ratios for clear sky conditions in Barcelona and other cities for comparison. This table confirms the presence of errors in the estimation of heat storage as residual, since 7.6 MJ m^{-2} day^{-1} would produce a heating of 1.5°K (for a stone surface 0.3 meter deep with a heat capacity of 1.5 MJm^{-3}). As would be expected, given the massive character of the urban fabric of central Barcelona, the heat storage dominates and is only comparable to that of central Mexico City (Oke et al, 1999) and to a lesser extent also to an industrial district in Vancouver. The relatively moist sea breeze and the presence of tree-lined streets in the vicinity of the site are reflected in a rather small heat flux amount (10% of net radiation), however small, it is twice as high as that observed in Mexico City. Given the small evaporation, the main energy sharing is between the two sensible heat fluxes: conduction into the buildings and ground (ΔQ_S=56%) and convection to the urban air (34%) (Tables 3 and 4).

VIII. CONCLUDING REMARKS

Heat storage is the largest energy sink for daylight time in Barcelona, peaking around 12:00 local time and remaining large in the afternoon, whereas the convective heat flux reached a plateau at about noon, remaining high until about 16:00 h (solar time) and staying positive well into the early evening.

The daytime $\Delta Q_S/Q^*$ ratio found for Barcelona, with that of Central Mexico City, is the largest of any central urban area (densely packed old buildings and with scarce vegetation) that has been studied. The Bowen ratio value is correspondingly almost as high (7.1) as that observed in Mexico City (9.9). A glance at Table 4 shows that the dense central quarters of Barcelona and Mexico City show similar energy partitioning in which heat storage dominates in contrast to most other studies of low density developed North American cities, with surface water availability. Evaporation is weak at all times mainly during the daytime due to advected moisture from the ocean and a relative presence of urban green.

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