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THE ENERGY BALANCE OF CENTRAL BARCELONA (SPAIN)

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1. INTRODUCTION

It is well established that substitution of natural land sufaces by urban elements induces changes of the local climate. Alteration of the land surfaces by urbanization characterizes 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 solar energy falling on the urban fabric is partitioned. The energy balance of a city can be expressed as

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

Where Q* is the net all-wave radiation, QF is the anthropogenic heat flux, Q_H is the sensible heat flux, QE is the latent heat flux, ΔQ_S is the net storage heat flux and ΔQ_A is the net horizontal advection. Most studies on energy partitioning in urban areas have been undertaken in suburban areas in Northamerica. In this paper the energy balance of a coastal city on the Mediterranean sea is presented.

2. GEOGRAPHICAL LOCATION AND CLIMATE

The city of Barcelona lies on the Mediterranean coastal plain of Spain near the border with France. With a population of about 3 million the city has a typical semiarid (BS) Mediterranean climate with a rainy period in autumn (600 mm/yr). Summer temperatures may on occasions rise to near 30-35 °C in July and August. 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 study and compare results with those obtained in other cities with similar (or contrasting) urban morphology and geographical location.

3. URBAN SETTING

The observation site is located on the southern edge of the central section of the city described as El Ensanche (The widening) an end-of-XIXth century urbanization characterized by wide straight roads lined with two or more rows of trees. The SE sector is occupied by the medieval city with narrow streets bordering to the SE with 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 buildings surrounding the site are mixed commercial/residential and typical of much of the city.

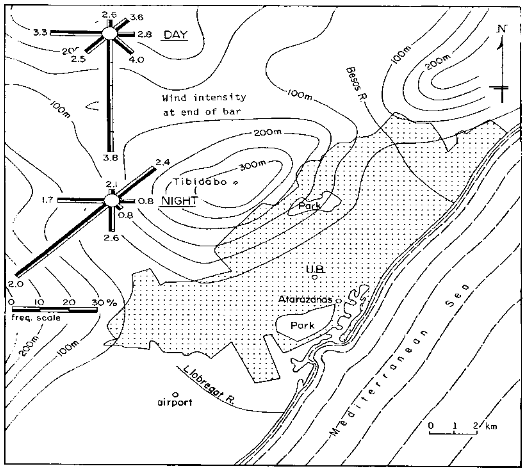

Fig. 1. Site location (UB) and wind roses (day and night) during experiment in June 2001 in Barcelona.

4. INSTRUMENTATION

The instruments were mounted on a 9m mast on the roof of the University of Barcelona, a 3 storey old building. 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 listed in Table 1 were calibrated in the instrumentation department Center Atmospheric Sciences (UNAM). They were fixed at the various heights above the roof as shown in Table 1.

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 dir.	Wind vane RM Young	9.0 m	Degrees (azimuth)
Qg, global rad.	Pyranometer Licor	3.2 m	W/m^2
Q*, net all-wave rad.	Net radiometer Campbell	8.0 m	W/m^2
Qh, sensible heat flux	Sonic anemometer Campbell	8.0 m	W/m^2
Qe, latent heat flux	Krypton hygrometer Campbell	8.0 m	W/m^2
T, air temp.	Thermometer Vaissala	3.8 m	°C
HR, rel. humidity.	Hygrometer Vaissala	3.8 m	%
W, vertical wind vel.	Sonic anemometer	9.0 m	m/s

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5. SURFACE LAYER CONDITIONS

5.1 ***Radiation***

The visual area covered by the net radiometer was estimated considering an angle of 85º around the vertical in such a manner that the maximum radius is

Rmax = 11.43 (h-hd) = 240 m 1)

where
h – height of sensor
hd – displacement height

hd = (Σ Aihi) / (Σ Ai)
where
Ai – building area
hi – height (m)

An iterative procedure was applied starting with r= 1 km to finally obtain an inferior visual radius for the net radiometer of 240 m.
Mean surface net long-wave emission values Qb were estimated and therefore the average albedo of the surface (a). Relationship between global radiation (Qg) and net radiation (Q*) is:

Q* = (1-a) Qg – Qb 3)

Qb may be estimated by linear regression (77 cases, daytime every half hour). The correlation coefficient was 0.9920, to obtain:

Q* = 0.68 Qg – 27 w/m2 4)

Thus the average surface albedo at the site during the observation period was 0.32 and the mean net diurnal long wave emission was 27 W/m2.

*5.2 **Temperature, humidity and wind conditions**.*

Table 2 shows average temperature, humidity and wind conditions that prevailed during the experiment. Temperature contrasts between day/night were small while intensity of wind decreased to about half the daytime value. As expected, the night relative humidity increased with the lower nocturnal temperatures of the land breeze.

	Horizontal wind (m/s)	Wind vertical component (m/s)	RH	T ºC
All cases	2.8	0.13	61	23.7
Day (Q*>0)	3.4	0.17	52	24.2
Night	1.6	0.05	79	20.9

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

5.3 Surface layer characteristics

Table 3 shows values of basic properties of the surface layer, considering several stability conditions.

Table 3. Fundamental characteristics of the roughness layer during the experiment.

	Unstable atmos.	Neutral atmos.	Unstable atmos.
QH Turbulent sensible heat flux (w/m2)	>0 practically >10 W/m2	=0 (actually between 0 and 10 W/m2	< 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

Results in table 3 show a clear congruity among the variables: instability conditions are reflected in higher values of the friction velocity, roughness height and surface layer depth.
Negative values of the Monin-Obukov length indicate the height at which flotation forces are balanced by turbulent impulse.

6. 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. 3).
The daytime period is characterized by higher peak values of net radiation (around 640 W/m2) in a practically smog-free atmosphere as compared with those observed in a tropical region like Mexico City (440 W/m^2) where the pollution layer attenuates short wave radiation.

Table 4. Summary of mean energy balance fluxes for clear sky conditions, when Q*>0 , in Barcelona and other cities. All quantities are non dimensional.

	DL (hs)	**Obs. period**	**Q_H/Q***	**Q_E/Q***	**Δ Q_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
+ L.A. (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, 1995.

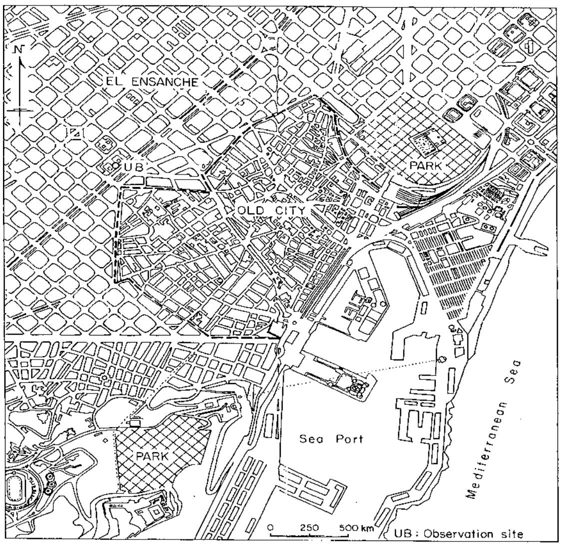

Fig. 2. Map of central Barcelona showing location of observation site.

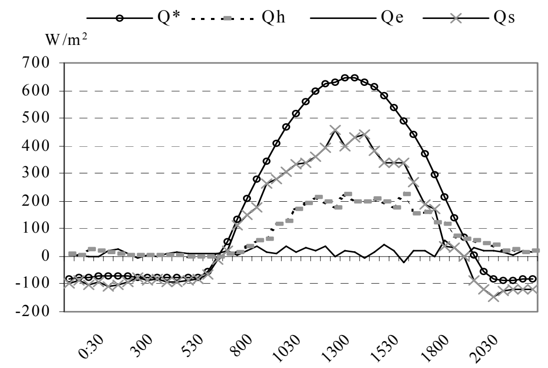

Fig. 3. Avg. fluxes for the Univ.Barcelona site for 16, 19-21 June 2001. Solar time.

While during the night the net radiation loss is large (around –90 W/m2) the storage release supplies energy equivalent to a somewhat larger amount of the net radiation.

Table 4 summarizes energy balance fluxes for clear sky conditions in Barcelona and other cities for comparison.

As would be expected and 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 heat flux which, albeit small (10%) is double that observed in Mexico City. Given the small evaporation the main energy sharing centers between the two sensible heat fluxes: conduction into the buildings and ground (ΔQ_S=56%) and convection of the urban air (34%) (Table 4).

CONCLUDING REMARKS

Heat storage is the largest energy sink for daylight hours in Barcelona, peaking around 12:00 hs remaining large in the afternoon whereas the convective flux reached a plateau at about noon, remaining high until about 16:00 hs and remaining positive well into the early evening.

The daytime $\Delta QS/Q^*$ ratio found for Barcelona (together with that corresponding to Mexico City) is one of the largest of any central urban area (heavily built up 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 dry heavily built-up central quarters of Barcelona and Mexico City show similar energy partitioning in which heat storage dominates in contrast (with exceptions) to other studied sparsely built-up Northamerican cities with surface water availability. Evaporation is weak at all times in spite of daytime advected moisture from the ocean and relative presence of urban green.

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