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POTENTIAL OF RADIATIVE COOLING IN SOUTHERN EUROPE

A. ARGIRIOU,[1] M. SANTAMOURIS,[2] C. BALARAS[1] and S. JETER[3]

[1]*Protechna Ltd, 87 Themistokleous st., GR-106 83 Athens, Greece*
[2]*University of Athens, Physics Dept, Laboratory of Meteorology, Ippocratous 33, 106 80 Athens, Greece*
[3]*The George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, Georgia, U.S.A.*

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Research on passive and low energy architecture has been recently oriented towards passive techniques in order to satisfy the cooling needs of buildings. One of the techniques which has been considered is radiative cooling. The potential of radiative cooling mainly in the United States has already been evaluated. However, a similar attempt has not been made for the southern European countries, where the weather in summer is very hot and passive cooling applications could make a significant contribution to the achievement of thermal comfort in buildings.

This paper investigates the feasibility of applying radiative cooling techniques in southern European countries by presenting the results of the calculations of the sky temperature depression and of the performance of a typical radiative flat plate air cooler. These calculations were based on mean monthly weather data available for 28 southern European cities, covering a range of latitudes between 34° and 46°. Available data from some southeastern U.S. cities, have also been used. This allowed for a comparative study on the performance of radiative cooling systems between southern Europe and the southeastern United States. The results have shown that radiative cooling could be applied successfully in most south European locations.

KEY WORDS: Passive cooling, Radiative cooling.

INTRODUCTION

Energy consumption for cooling in buildings has been increasing constantly during the last decade. Especially in southern European countries where the hot summer conditions extend the cooling period from May through September, the problem of achieving thermal comfort in buildings is of great importance. Actually, the cooling requirements have been primarily satisfied by active systems and the use of air conditioning systems (split units) have become highly popular. In Greece, for example, the imports of conventional air conditioning systems have increased by 900% from 1987 to 1990.

Energy economy and ecological constraints, however, have oriented the research in passive and low energy architecture towards the alternative solutions offered by passive and hybrid cooling techniques. These methods have been under investigation in the United States and in Israel for more than fifteen years. However, in Europe similar research has only been recently initiated with some research and development programs currently underway.[1]

Passive cooling techniques are the processes of heat dissipation which occur naturally, that is without utilizing mechanical components or energy inputs. Using a broader definition, one may include in passive cooling the mechanically assisted heat transfer techniques which enhance the natural cooling processes.[2] In this case, these are called hybrid cooling techniques.

Radiative cooling is a technique which can be used as either a passive or as a hybrid one. It is based on the fact that every object being at a temperature higher than 0 K emits energy in the form of electromagnetic radiation. In the case of radiative cooling, the building envelope, or another appropriate device, is cooled by dissipating infrared radiation to the sky which acts as a low temperature environmental heat sink.

Table 1. Number of events for a given sky temperature depression in May

LOCATION	WEATHER CONDITION	SKY TEMPERATURE DEPRESSION (C) 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
AJACCIO, IT	OPTIMUM															1	2	2	2	2			
(LAT=41.93N)	AVERAGE										2	2	1	2	2								
ALMERIA, SP	OPTIMUM															3	2	2	3	1			
(LAT=36.85N)	AVERAGE												4	2	2	3							
ANCONA, IT	OPTIMUM																3	3	2	1			
(LAT=43.62N)	AVERAGE										1	3	2	3									
ATHENS, GR	OPTIMUM																	4	2	3			
(LAT=37.9N)	AVERAGE													3	2	2	2						
ATLANTA, USA	OPTIMUM												1	2	1		1	1	1	1	1	2	
(LAT=33.65N)	AVERAGE								2	1	1	1	1		1	1	2	1					
BARCELONA, SP	OPTIMUM																	4	3	2			
(LAT=41.38N)	AVERAGE													4	2	3							
BRINTISI, IT	OPTIMUM															3	2	2	2				
(LAT=40.65N)	AVERAGE											2	2	2	2	1							
CAGLIARI, IT	OPTIMUM																	2	3	2	2		
(LAT=39.23N)	AVERAGE													2	3	2	2						
CATANIA, IT	OPTIMUM																		4	2	3		
(LAT=37.47N)	AVERAGE														2	3	2	2					
CHARLESTON, USA	OPTIMUM									1	1	1	1	1	1		1	1	1	2			
(LAT=32.9N)	AVERAGE				1	1	1	1	1		1	1	1		2	1							
DUBROVNIC, YU	OPTIMUM																	4	3	2			
(LAT=42.63N)	AVERAGE												2	3	2	2							
GENOVA, IT	OPTIMUM																		6	3			
(LAT=44.40N)	AVERAGE													5	3	1							
GIBRALTAR	OPTIMUM														3	3	2	3					
(LAT=36.15N)	AVERAGE											4	2	2	3								
IERAPETRA, GR	OPTIMUM															3	3	3	2				
(LAT=35.00)	AVERAGE												4	3	2	2							
LIVORNO, IT	OPTIMUM																	3	2	3	1		
(LAT=43.55)	AVERAGE												1	3	2	2	1						
MARSEILE, FR	OPTIMUM																2	2	2	1	3		
(LAT=43.30N)	AVERAGE											1	2	2	1	2	1						
MAIMI, USA	OPTIMUM										1	2	1	2	1	1	2	1					
(LAT=25.8N)	AVERAGE					1	2	1	1	1	1	2	2										
MILOS, GR	OPTIMUM																4	3	2	2			
(LAT=36.44N)	AVERAGE													4	3	2	2						
NAPOLI, IT	OPTIMUM																	4	2	3			
(LAT=40.68)	AVERAGE												2	3	2	2							
NICE, PR	OPTIMUM																3	3	2	1			
(LAT=43.68N)	AVERAGE												4	2	2	1							
NICOSIA, CY	OPTIMUM																1	3	1	2	1	2	1
(LAT=35.15N)	AVERAGE													1	3	1	2	1	2	1			
PALMA, SP	OPTIMUM																3	1	2	2	1		
(LAT=39.57N)	AVERAGE												2	2	2	1	2						
PAPHOS, CY	OPTIMUM															3	2	1	2	2	1		
(LAT=34.75N)	AVERAGE												4	1	2	1	2	1					
PERPIGNANT, FR	OPTIMUM																	2	3	2	2		
(LAT=42.73N)	AVERAGE										1	3	2	1	2								
RALEIGH, USA	OPTIMUM											2	1	1		1	1		1	1	1	2	
(LAT=35.87N)	AVERAGE						2	1		1	1		1	1		1	2	1					
ROMA, IT	OPTIMUM																	1	3	2	2	1	
(LAT=41.9N)	AVERAGE													3	2	2	2						
SPLIT, YU	OPTIMUM																3	3	3				
(LAT=43.52N)	AVERAGE											3	3	3									
THESALONIKI, GR	OPTIMUM																3	2	2	2			
(LAT=40.33N)	AVERAGE											1	3	1	2	2							
TRIESTE, IT	OPTIMUM																	2	3	3	1		
(LAT=45.65N)	AVERAGE												4	2	3								
VALLETTA, IT	OPTIMUM																	9	2				
(LAT=35.90N)	AVERAGE													9	2								
VALENCIA, SP	OPTIMUM																1	3	2	3			
(LAT=39.47N)	AVERAGE												2	3	2	2							
VENEZIA, IT	OPTIMUM																2	3	2	2			
(LAT=45.43N)	AVERAGE											3	2	3	1								

The potential of radiative coo
information is given in [3]. How
studies of radiative cooling for tl
estimate.[4]

This paper aims to satisfy the
cooling around the northern par
include the sky temperature de
the feasibility of radiative coo
energy for a simple flat plate rac
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These calculations have been
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mance of the same flat plate air
Atlanta (GA), Miami (FL), Cha

MODEL PRESENTATION

Sky Temperature Depression

The atmosphere emits thermal
with a spectral distribution very
equal to the dry bulb temperat
emission of the atmosphere is
transitions of the asymmetrical
composed. These molecules are
The symmetrical molecules, O_2
are transparent to infrared radi
dioxide have a few transitions i
for all practical reasons, the at
spectral region, and is usually ca

The influence of the various a
of the atmosphere is as follows:

– More than 90% of the tota
altitude. The contribution of
H_2O + continuum, 2.8% for C

– Ozone has a nearly constan
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where its concentration is pre

– The atmospheric window i
of CO_2. The carbon dioxid
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variation, because the emis
emission spectrum of water v

– The contribution of all oth

If an object on the earth's su

The potential of radiative cooling has been evaluated for the United States and information is given in [3]. However, until now there have not been any extensive studies of radiative cooling for the southern European countries, other than a first estimate.[4]

This paper aims to satisfy the lack of information on the potential of radiative cooling around the northern part of the Mediterranean basin. The calculated data include the sky temperature depression, which is the parameter for determining the feasibility of radiative cooling systems and the mean daily useful cooling energy for a simple flat plate radiative air cooler. The cooled air can then be used to satisfy part of a building's cooling needs.

These calculations have been based on meteorological data from 28 southern european locations,[5] listed in Table 1. The efficiency of this radiative cooling technique in southern Europe is compared with the efficiency that it could have in some locations of the southeastern United States. For this reason the performance of the same flat plate air cooler has been evaluated using climatic data[6] for Atlanta (GA), Miami (FL), Charleston (NC) and Raleigh (SC).

MODEL PRESENTATION

Sky Temperature Depression

The atmosphere emits thermal radiation, except in the spectral region 8–13 μm, with a spectral distribution very close to the one of a blackbody at a temperature equal to the dry bulb temperature of the air close to the ground. The thermal emission of the atmosphere is mainly due to the vibrational and rotational transitions of the asymmetrical molecules from which the earth's atmosphere is composed. These molecules are mainly water vapour, carbon dioxide, and ozone. The symmetrical molecules, O_2 and N_2, which compose 99% of the atmosphere, are transparent to infrared radiation (beyond 3 μm).[7] Water vapour and carbon dioxide have a few transitions in the spectral region of 8–13 μm. Consequently, for all practical reasons, the atmosphere can be considered transparent in this spectral region, and is usually called "atmospheric window".

The influence of the various atmospheric components to the thermal radiation of the atmosphere is as follows:[7]

- More than 90% of the total emitted radiation comes from the first 5 km in altitude. The contribution of each constituent to the total flux is 95.7% for H_2O + continuum, 2.8% for CO_2 (including CH_4 and N_2O), and 1.5% for O_3.
- Ozone has a nearly constant peak of emission at 9.6 μm, (near the centre of the atmospheric window), as it comes from the absorption in the stratosphere where its concentration is predominant.
- The atmospheric window is limited at about 14 μm because of the emission of CO_2. The carbon dioxide concentration is practically constant and no significant variation of the emitted thermal energy has been observed from it's variation, because the emission spectrum of CO_2 is superimposed to the emission spectrum of water vapour.
- The contribution of all other elements of the atmosphere is very small.

If an object on the earth's surface emits thermal radiation within the range of the atmospheric window, assuming that the atmospheric conditions are such that the atmospheric window is "open" (i.e. low relative humidity and clear sky), then its temperature decreases. A radiator performs better under clear sky conditions than under partly cloudy or average sky conditions. This was only to be expected since under clear sky conditions, the sky thermal radiation is low, enabling the radiator to emit more energy towards the low temperature heat sink than under average sky conditions. Increased amounts of clouds absorb and reemit the infrared radiation. As a result, it slows the rate of radiative cooling from the plate collector to the night sky.

The determinant parameter in evaluating the performance of a radiative cooling system is the sky temperature depression. This is defined as the difference of the ambient air temperature minus the "sky temperature" (i.e. the temperature of the blackbody having the same spectral distribution as the sky).

The sky temperature depression (DT_{sky}) is calculated by the following relation:

$$DT_{sky} = (1 - \varepsilon_{sky}^{1/4})T_a \tag{1}$$

where ε_{sky} = sky emissivity, and T_a = ambient temperature.

Many correlations are reported in the literature for calculating the sky emissivity. As it has been explained already, the major part of the thermal radiation that the sky emits is due to the water vapour; for this reason, an expression of the sky emissivity as a function of a parameter related to the water content is required. In this paper, the Berdahl and Martin relationship has been used for the clear sky emissivity:[8]

$$\varepsilon_{cs} = 0.711 + 0.56(T_{dp}/100) + 0.73(T_{dp}/100)^2 \tag{2}$$

where T_{dp} = dew point temperature, defined as:[9]

$$T_{dp} = C_3[\ln(\mathrm{RH}) + C_1]/\{C_2 - [\ln(\mathrm{RH}) + C_1]\} \tag{3}$$

where $C_1 = C_2 T_{dry}/(C_3 + T_{dry})$, $C_2 = 17.08085$, $C_3 = 234.175$, T_{dry} = ambient dry bulb temperature (°C), and RH = relative humidity $0 \leq \mathrm{RH} \leq 1$.

The calculations for the instantaneous clear sky emissivities were estimated using the following expression which takes into account the diurnal variation:[8]

$$\Delta\varepsilon_d = 0.013\cos\{2\pi t/24\} \tag{4}$$

where t = hour of the day.

The values of sky emissivity obtained by equations (2) and (4) are clear sky emissivities. Under cloudy skies the sky emissivity (ε_s) can be calculated by the following relationship:[8]

$$\varepsilon_s = \varepsilon_{cs}(1 + 0.0224n - 0.0035n^2 + 0.00028n^3) \tag{5}$$

where n = total opaque cloud amount ($0 \leq n \leq 1$)

Radiator Performance

The simulation of the operation of a typical flat plate air cooler was performed for an open loop radiative cooling system with an uncovered air collector whose surface is exposed to the atmosphere at night and cools the air that circulates through the system. The air cooler was assumed to be a horizontal 2 m long rectangular air duct. The dimensions of the flow section were 1 m by 0.20 m. The radiator was considered to be a 0.003 m stainless steel plate, having an emittance of 0.90 in the I.R. bandwidth. It was assumed that the cooler was functioning only during the night time with an air velocity through the radiator set at 2.5 m/sec. The radiator was assumed to be horizontal, because it has been shown that sky radiation is less in the region of zenith than near the horizon.[8] Simulations have been also carried out for the same system covered with a wind screen in order to minimize convective losses.

The useful cooling energy and the outlet temperature of the air provided by the radiator are calculated based on the work by Ito and Miura:[10]

Cooling power of a radiator

The net heat flux (q_r) of a nonselective radiator at temperature (T_r) is calculated as a linear function of an effective heat transfer coefficient (h_e) and a minimum threshold temperature (T_{th}), as follows:

$$q_r = h_e(T_r - T_{th}) \tag{6}$$

where h_e = effective heat transfer coefficient $= h + 4\varepsilon\sigma T_s^3$ and T_{th} = minimum threshold temperature $= T_s - \varepsilon q_o / h_e$.

The minimum threshold temperature is the lowest temperature attainable by the radiator. The convective heat transfer coefficient (h) is a function of the wind velocity (V) and it is calculated by the following expressions:[11]

Radiator with no wind screen:

$$h = 5.7 + 3.8V \qquad V \leq 4\ \text{m/s} \tag{7}$$

$$h = 7.3V^{0.8} \qquad V > 4\ \text{m/s} \tag{8}$$

Radiator with wind screen:

$$h = 0.5 + 1.2V^{0.5} \tag{9}$$

The net radiative power of a blackbody (q_o) at the ambient temperature (T_a) is given by:

$$q_o = \sigma T_a^4 - q_s \tag{10}$$

where q_s = sky irradiance $= \varepsilon_{sky}\sigma T_a^4$

Fluid temperature

The problem of calculating the temperature of the heat transfer fluid flowing through a one-dimensional path in a radiator has been solved by Ito and Miura[10] in the same way as the case of a solar collector, Duffie and Beckman,[12] and is given by:

$$T_{fo} - T_{th} = (T_{fi} - T_{th}) \exp(-U_p A / m c_p) \tag{11}$$

where T_{fi} = inlet temperature of the heat transfer fluid, T_{fo} = outlet temperature of the heat transfer fluid, U_p = overall heat transfer coefficient, m = mass flow rate, c_p = specific heat at constant pressure, and A = surface of the radiator.

Equation (11) calculates the outlet temperature of the heat transfer fluid given that the minimum threshold temperature T_{th} is known. One should note that, the temperature dependence of the thermal properties of the radiator and the heat transfer fluid have also been taken into account in the numerical model.

The method used for calculating the useful cooling energy and the outlet temperature of the air provided by an uncovered radiator has been experimentally tested by Ito and Miura.[10] The theoretical and experimental results were found in excellent agreement. The net radiative power obtained by the measurements was 40–60 W/m^2 on clear nights in the summer and 60–80 W/m^2 in the fall and winter. The average temperature of the energy storage tank on clear nights became 2–5°C below the ambient temperature.

RESULTS

The model presented in the previous section has been used to calculate the sky temperature depression and the outlet air temperature which was used to determine the useful cooling energy of a flat plate radiative air cooler for various

Table 2. Number of events for a given sky temperature depression in June

LOCATION	WEATHER CONDITION	SKY TEMPERATURE DEPRESSION (C) 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
AJACCIO, IT	OPTIMUM															3	2	1	2	1			
(LAT=41.93N)	AVERAGE										1	2	2	1	2	1							
ALMERIA, SP	OPTIMUM														3	2	2	2					
(LAT=36.85N)	AVERAGE											3	2	2	2								
ANCONA, IT	OPTIMUM																4	3	2				
(LAT=43.62N)	AVERAGE											3	3	2	1								
ATHENS, GR	OPTIMUM																4	2	2	1			
(LAT=37.9N)	AVERAGE													2	3	2	2						
ATLANTA, USA	OPTIMUM										1	1	1	1	1	1	1	2					
(LAT=33.65N)	AVERAGE					1	1	1	1	1	1	1	1	1									
BARCELONA, SP	OPTIMUM															4	2	3					
(LAT=41.38N)	AVERAGE											3	3	2	1								
BRINTISI, IT	OPTIMUM														3	2	2	2					
(LAT=40.65N)	AVERAGE											3	2	2	2								
CAGLIARI, IT	OPTIMUM																2	2	2	2	1		
(LAT=39.23N)	AVERAGE													3	2	2	1	1					
CATANIA, IT	OPTIMUM																2	2	2	3			
(LAT=37.47N)	AVERAGE														4	2	1	2					
CHARLESTON, USA	OPTIMUM									2	1	1		1	1	1	1	1					
(LAT=32.9N)	AVERAGE			1	1	1	1		1	1	1	1	1										
DUBROVNIC, YU	OPTIMUM															3	2	3	1				
(LAT=42.63N)	AVERAGE												4	3	2								
GENOVA, IT	OPTIMUM																3	3	2	1			
(LAT=44.40N)	AVERAGE												4	2	3								
GIBRALTAR	OPTIMUM													3	2	2	2						
(LAT=36.15N)	AVERAGE										2	3	2	2									
IERAPETRA, GR	OPTIMUM															5	2	2					
(LAT=35.00)	AVERAGE													5	2	2							
LIVORNO, IT	OPTIMUM																4	3	2				
(LAT=43.55)	AVERAGE												4	2	2	1							
MARSEILE, FR	OPTIMUM															2	2	1	2	2			
(LAT=43.30N)	AVERAGE											1	2	2	1	2	1						
MAIMI, USA	OPTIMUM									2	1	2	1	1	1	2	1						
(LAT=25.8N)	AVERAGE			1	2	1	1	1	2	1	2												
MILOS, GR	OPTIMUM															1	4	3	1				
(LAT=36.44N)	AVERAGE														4	3	2						
NAPOLI, IT	OPTIMUM															2	3	2	2				
(LAT=40.68)	AVERAGE											1	4	2	2								
NICE, FR	OPTIMUM														3	3	2	1					
(LAT=43.68N)	AVERAGE										2	3	2	2									
NICOSIA, CY	OPTIMUM																2	2	1	2	1	1	
(LAT=35.15N)	AVERAGE														1	2	1	2	1	2			
PALMA, SP	OPTIMUM															3	2	2	1	1			
(LAT=39.57N)	AVERAGE											3	1	2	2	1							
PAPHOS, CY	OPTIMUM													1	2	2	1	2	1				
(LAT=34.75N)	AVERAGE											1	2	2	1	2	1						
PERPIGNANT, FR	OPTIMUM																3	2	2	2			
(LAT=42.73N)	AVERAGE										3	2	2	2									
RALEIGH, USA	OPTIMUM									1	1	1		1	1	1		1	2				
(LAT=35.87N)	AVERAGE				1	1		1	1	1		1	1	1	1								
ROMA, IT	OPTIMUM																1	3	2	1	2		
(LAT=41.9N)	AVERAGE												1	2	2	2	2						
SPLIT, YU	OPTIMUM																4	2	3				
(LAT=43.52N)	AVERAGE												4	2	3								
THESALONIKI, GR	OPTIMUM																3	2	2	2			
(LAT=40.33N)	AVERAGE													3	2	2	2						
TRIESTE, IT	OPTIMUM																4	3	2				
(LAT=45.65N)	AVERAGE											4	3	2									
VALLETTA, IT	OPTIMUM																7	2					
(LAT=35.90N)	AVERAGE												4	4	1								
VALENCIA, SP	OPTIMUM															2	3	2	2				
(LAT=39.47N)	AVERAGE											1	3	2	2	1							
VENEZIA, IT	OPTIMUM															3	2	3	1				
(LAT=45.43N)	AVERAGE										2	3	2	2									

locations of southern
simulations have been
one for average sky c
Tables 1 to 5 give t
the cooling season (N
reaches a given value
which can be very
applications at a give
An example is giv
(May–September) fo
for Ajaccio – France.

Table 3. Number of event

LOCATION	WEATHER CONDITION
AJACCIO, IT	OPTIMUM
(LAT=41.93N)	AVERAGE
ALMERIA, SP	OPTIMUM
(LAT=36.85N)	AVERAGE
ANCONA, IT	OPTIMUM
(LAT=43.62N)	AVERAGE
ATHENS, GR	OPTIMUM
(LAT=37.9N)	AVERAGE
ATLANTA, USA	OPTIMUM
(LAT=33.65N)	AVERAGE
BARCELONA, SP	OPTIMUM
(LAT=41.38N)	AVERAGE
BRINT'SI, IT	OPTIMUM
(LAT=40.65N)	AVERAGE
CAGLIARI, IT	OPTIMUM
(LAT=39.23N)	AVERAGE
CATANIA, IT	OPTIMUM
(LAT=37.47N)	AVERAGE
CHARLESTON, USA	OPTIMUM
(LAT=32.9N)	AVERAGE
DUBROVNIC, YU	OPTIMUM
(LAT=42.63N)	AVERAGE
GENOVA, IT	OPTIMUM
(LAT=44.40N)	AVERAGE
GIBRALTAR	OPTIMUM
(LAT=36.15N)	AVERAGE
IERAPETRA, GR	OPTIMUM
(LAT=35.00)	AVERAGE
LIVORNO, IT	OPTIMUM
(LAT=43.55)	AVERAGE
MARSEILE, FR	OPTIMUM
(LAT=43.30N)	AVERAGE
MAIMI, USA	OPTIMUM
(LAT=25.8N)	AVERAGE
MILOS, GR	OPTIMUM
(LAT=36.44N)	AVERAGE
NAPOLI, IT	OPTIMUM
(LAT=40.68)	AVERAGE
NICE, FR	OPTIMUM
(LAT=43.68N)	AVERAGE
NICOSIA, CY	OPTIMUM
(LAT=35.15N)	AVERAGE
PALMA, SP	OPTIMUM
(LAT=39.57N)	AVERAGE
PAPHOS, CY	OPTIMUM
(LAT=34.75N)	AVERAGE
PERPIGNANT, FR	OPTIMUM
(LAT=42.73N)	AVERAGE
RALEIGH, USA	OPTIMUM
(LAT=35.87N)	AVERAGE
ROMA, IT	OPTIMUM
(LAT=41.90N)	AVERAGE
SPLIT, YU	OPTIMUM
(LAT=43.52N)	AVERAGE
THESALONIKI, GR	OPTIMUM
(LAT=40.33N)	AVERAGE
TRIESTE, IT	OPTIMUM
(LAT=45.65N)	AVERAGE
VALETTA, IT	OPTIMUM
(LAT=35.90N)	AVERAGE
VALENCIA, SP	OPTIMUM
(LAT=39.47N)	AVERAGE
VENEZIA, IT	OPTIMUM
(LAT=45.43N)	AVERAGE

locations of southern Europe and southeastern United States. Two series of simulations have been performed for each location; one for optimum (clear) and one for average sky conditions.

Tables 1 to 5 give the total number of hours for a typical day in each month of the cooling season (May–September) for which the sky temperature depression reaches a given value. These data can also be presented in the form of histograms which can be very useful for determining the feasibility of radiative cooling applications at a given location.

An example is given in Figure 1, where the corresponding monthly values (May–September) for the sky temperature depression distribution is illustrated for Ajaccio – France, Raleigh – U.S.A., Athens – Greece and Nicosia – Cyprus.

Table 3. Number of events for a given sky temperature depression in July

LOCATION	WEATHER CONDITION	SKY TEMPERATURE DEPRESSION (C) 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
AJACCIO, IT	OPTIMUM														3	2	1	2	1				
(LAT=41.93N)	AVERAGE											3	2	1	2	1							
ALMERIA, SP	OPTIMUM													3	2	2	2						
(LAT=36.85N)	AVERAGE										3	2	2	2									
ANCONA, IT	OPTIMUM															4	2	2	1				
(LAT=43.62N)	AVERAGE											4	2	2	1								
ATHENS, GR	OPTIMUM																4	2	2	1			
(LAT=37.9N)	AVERAGE															4	2	2	1				
ATLANTA, USA	OPTIMUM									1	1	1	1	1	1	1	2						
(LAT=33.65N)	AVERAGE				1	1	1	1	1	1	1	2											
BARCELONA, SP	OPTIMUM														2	3	3	1					
(LAT=41.38N)	AVERAGE											4	3	2									
BRINT'SI, IT	OPTIMUM													3	2	2	2						
(LAT=40.65N)	AVERAGE											3	2	2	2								
CAGLIARI, IT	OPTIMUM															1	3	2	2	1			
(LAT=39.23N)	AVERAGE													1	3	2	2	1					
CATANIA, IT	OPTIMUM																4	2	3				
(LAT=37.47N)	AVERAGE														3	2	2	2					
CHARLESTON, USA	OPTIMUM								2	1	1	1	1	1	1	1	2						
(LAT=32.9N)	AVERAGE		1	2	1	1		1	1	1	2	1											
DUBROVNIC, YU	OPTIMUM														3	3	2	1					
(LAT=42.63N)	AVERAGE												4	2	3								
GENOVA, IT	OPTIMUM																5	3	1				
(LAT=44.40N)	AVERAGE												3	3	3								
GIBRALTAR	OPTIMUM												2	3	2	2							
(LAT=36.15N)	AVERAGE									1	3	2	2	1									
IERAPETRA, GR	OPTIMUM															5	2	2					
(LAT=35.00)	AVERAGE														4	2	3						
LIVORNO, IT	OPTIMUM															4	2	3					
(LAT=43.55)	AVERAGE											2	3	2	2								
MARSEILE, FR	OPTIMUM														1	2	2	1	2	1			
(LAT=43.30N)	AVERAGE												3	1	2	1	2						
MAIMI, USA	OPTIMUM									2	2	1	1	1	2	2							
(LAT=25.8N)	AVERAGE				3	1	1	1	2	1	2												
MILOS, GR	OPTIMUM															5	3	1					
(LAT=36.44N)	AVERAGE														4	3	2						
NAPOLI, IT	OPTIMUM														1	4	2	2					
(LAT=40.68)	AVERAGE											1	4	2	2								
NICE, FR	OPTIMUM													3	2	3	1						
(LAT=43.68N)	AVERAGE										4	2	2	1									
NICOSIA, CY	OPTIMUM															2	2	1	1	2	1		
(LAT=35.15N)	AVERAGE														1	2	2	1	1	2			
PALMA, SP	OPTIMUM														3	1	2	2	1				
(LAT=39.57N)	AVERAGE											2	2	1	2	2							
PAPHOS, CY	OPTIMUM												2	2	1	2	2						
(LAT=34.75N)	AVERAGE										2	2	1	2	1	1							
PERPIGNANT, FR	OPTIMUM															3	2	1	2	1			
(LAT=42.73N)	AVERAGE										1	2	2	2	2								
RALEIGH, USA	OPTIMUM									2	1		1	1	1	1	1	1					
(LAT=35.87N)	AVERAGE				2		1	1	1	1		1	2										
ROMA, IT	OPTIMUM																3	2	2	2			
(LAT=41.90N)	AVERAGE													3	2	2	2						
SPLIT, YU	OPTIMUM															3	3	2	1				
(LAT=43.52N)	AVERAGE												3	3	2	1							
THESALONIKI, GR	OPTIMUM														2	2	2	2	1				
(LAT=40.33N)	AVERAGE												2	2	2	2	1						
TRIESTE, IT	OPTIMUM																5	3	1				
(LAT=45.65N)	AVERAGE											1	4	3	1								
VALETTA, IT	OPTIMUM														6	3							
(LAT=35.90N)	AVERAGE												4	5									
VALENCIA, SP	OPTIMUM														3	3	2	1					
(LAT=39.47N)	AVERAGE										2	3	2	2									
VENEZIA, IT	OPTIMUM														3	2	2	2					
(LAT=45.43N)	AVERAGE										2	3	2	2									

Table 4. Number of events for a given sky temperature depression in August

LOCATION	WEATHER CONDITION	SKY TEMPERATURE DEPRESSION (C)																					
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
AJACCIO, IT	OPTIMUM													2	2	2	1	2	2				
(LAT=41.93N)	AVERAGE										2	2	2	1	2	2							
ALMERIA, SP	OPTIMUM												3	2	2	2	2						
(LAT=36.85N)	AVERAGE									3	2	2	2	2									
ANCONA, IT	OPTIMUM														3	2	3	2	1				
(LAT=43.62N)	AVERAGE											5	2	2	2								
ATHENS, GR	OPTIMUM															3	2	2	3	1			
(LAT=37.9N)	AVERAGE														3	3	2	2	1				
ATLANTA, USA	OPTIMUM									2	1	1	1	1	1	1	1	2					
(LAT=33.65N)	AVERAGE				2	1	1	1	1	1		2	1	1									
BARCELONA, SP	OPTIMUM														6	2	3						
(LAT=41.38N)	AVERAGE										5	2	3	1									
BRINTISI, IT	OPTIMUM													5	2	3	1						
(LAT=40.65N)	AVERAGE											5	2	2	2								
CAGLIARI, IT	OPTIMUM															4	2	2	2	1			
(LAT=39.23N)	AVERAGE													3	3	1	2	2					
CATANIA, IT	OPTIMUM																5	2	3	1			
(LAT=37.47N)	AVERAGE															5	2	3	1				
CHARLESTON, USA	OPTIMUM								2	1	1	1	1	1	1	1	2						
(LAT=32.9N)	AVERAGE		1	1	1	1	1	1	1	1	1	2											
DUBROVNIC, YU	OPTIMUM															4	2	3	2				
(LAT=42.63N)	AVERAGE													4	3	2	2						
GENOVA, IT	OPTIMUM															4	4	2	1				
(LAT=44.40N)	AVERAGE												7	2	2								
GIBRALTAR	OPTIMUM												3	2	2	2	2						
(LAT=36.15N)	AVERAGE									2	3	1	2	3									
IERAPETRA, GR	OPTIMUM														4	3	2	2					
(LAT=35.00)	AVERAGE													4	3	2	2						
LIVORNO, IT	OPTIMUM															5	3	2	1				
(LAT=43.55)	AVERAGE											3	3	2	3								
MARSEILE, FR	OPTIMUM														3	2	1	2	2	1			
(LAT=43.30N)	AVERAGE											3	2	2	1	2	1						
MAIMI, USA	OPTIMUM									2	2	1	1	1	2	2							
(LAT=25.8N)	AVERAGE				3	1	1	1	1	2	2												
MILOS, GR	OPTIMUM														3	3	3	2					
(LAT=36.44N)	AVERAGE													3	3	3	2						
NAPOLI, IT	OPTIMUM														3	3	2	2	1				
(LAT=40.68)	AVERAGE											3	3	2	2	1							
NICE, FR	OPTIMUM													5	2	2	2						
(LAT=43.68N)	AVERAGE										5	2	2	2									
NICOSIA, CY	OPTIMUM														3	2	1	1	2	2			
(LAT=35.15N)	AVERAGE													3	1	2	1	2	2				
PALMA, SP	OPTIMUM													3	2	2	2	2					
(LAT=39.57N)	AVERAGE										4	2	1	2	2								
PAPHOS, CY	OPTIMUM												2	2	2	1	2	2					
(LAT=34.75N)	AVERAGE										3	1	2	2	1	2							
PERPIGNANT, FR	OPTIMUM														2	3	2	2	2				
(LAT=42.73N)	AVERAGE									2	2	2	2	3									
RALEIGH, USA	OPTIMUM								1	2		1	1	1	1	1	1	1	1				
(LAT=35.87N)	AVERAGE			1	1	1	1	1	1		1	1	1	2									
ROMA, IT	OPTIMUM															3	2	2	2	2			
(LAT=41.90N)	AVERAGE												1	3	2	2	2	1					
SPLIT, YU	OPTIMUM															4	2	3	2				
(LAT=43.52N)	AVERAGE												4	3	2	2							
THESALONIKI, GR	OPTIMUM														3	2	1	2	1	2			
(LAT=40.33N)	AVERAGE											1	3	1	2	1	2	1					
TRIESTE, IT	OPTIMUM															3	4	2	2				
(LAT=45.65N)	AVERAGE												6	2	3								
VALETTA, IT	OPTIMUM													8	3								
(LAT=35.90N)	AVERAGE										6	4	1										
VALENCIA, SP	OPTIMUM														4	3	2	2					
(LAT=39.47N)	AVERAGE										3	3	2	3									
VENEZIA, IT	OPTIMUM														3	3	2	2	1				
(LAT=45.43N)	AVERAGE										3	2	2	2	2								

Athens is the most appropriate site among the ones presented in this figure for radiative cooling applications, because the sky temperature depression seldom decreases below 14°C. It is important to note here the difference between the four cities with regard to the number of continuous hours during which high temperature depression values are obtained.

For Athens and Nicosia, the sky temperature depression values are at the same levels but Athens exhibits longer number of continuous hours for a given temperature depression. The highest sky temperature depression values for Ajaccio are observed for almost the same number of hours compared to Nicosia, but these values are lower than the values of sky temperature depression obtained in Nicosia. Finally Raleigh, which has the highest relative humidity during the

Table 5. Number of events for a given sky temperature depression in September

LOCATION	WEATHER CONDITION	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
											SKY TEMPERATURE DEPRESSION (C)												
AJACCIO, IT	OPTIMUM														3	2	2	2	2				
(LAT=41.93N)	AVERAGE										4	1	2	2	2								
ALMERIA, SP	OPTIMUM													3	2	2	3	1					
(LAT=36.85N)	AVERAGE										4	2	2	2	1								
ANCONA, IT	OPTIMUM																6	2	3				
(LAT=43.62N)	AVERAGE											5	3	3									
ATHENS, GR	OPTIMUM																4	3	2	2			
(LAT=37.9N)	AVERAGE														5	2	3	1					
ATLANTA, USA	OPTIMUM											2	2	1		1	1	2	1	1			
(LAT=33.65N)	AVERAGE						2	1	1	1	1	1	1	1	2								
BARCELONA, SP	OPTIMUM															6	2	3					
(LAT=41.38N)	AVERAGE											5	3	2	1								
BRINTISI, IT	OPTIMUM													4	2	3	2						
(LAT=40.65N)	AVERAGE									2	3	2	3	1									
CAGLIARI, IT	OPTIMUM															3	3	2	2	1			
(LAT=39.23N)	AVERAGE												5	2	2	2							
CATANIA, IT	OPTIMUM																3	3	2	3			
(LAT=37.47N)	AVERAGE													2	3	3	2	1					
CHARLESTON, USA	OPTIMUM									2	1	1	1	1	1	1	1	2					
(LAT=32.9N)	AVERAGE				2	1	1	1	1		1	1	2	1									
DUBROVNIC, YU	OPTIMUM																6	3	2				
(LAT=42.63N)	AVERAGE													6	2	3							
GENOVA, IT	OPTIMUM																6	3	1				
(LAT=44.40N)	AVERAGE											2	5	3	1								
GIBRALTAR	OPTIMUM												2	3	2	2	2						
(LAT=36.15N)	AVERAGE									2	3	2	2	2									
IERAPETRA, GR	OPTIMUM														3	3	3	2					
(LAT=35.00)	AVERAGE												4	3	2	2							
LIVORNO, IT	OPTIMUM																5	2	3	1			
(LAT=43.55)	AVERAGE												4	3	2	2							
MARSEILE, FR	OPTIMUM														3	2	2	1	3				
(LAT=43.30N)	AVERAGE										2	2	2	1	2	2							
MAIMI, USA	OPTIMUM									2	2	1	1	2	1	2							
(LAT=25.8N)	AVERAGE			1	2	[illegible]	2	1	1	2	1												
MILOS, GR	OPTIMUM															4	3	3	1				
(LAT=36.44N)	AVERAGE													5	2	3	1						
NAPOLI, IT	OPTIMUM															4	3	3	1				
(LAT=40.68)	AVERAGE											4	3	3	1								
NICE, FR	OPTIMUM														5	2	2	2					
(LAT=43.68N)	AVERAGE										4	3	2	2									
NICOSIA, CY	OPTIMUM														3	1	2	1	1	2	1		
(LAT=35.15N)	AVERAGE												1	2	2	1	1	2	2				
PALMA, SP	OPTIMUM													3	2	2	2	2					
(LAT=39.57N)	AVERAGE									3	2	1	2	2	1								
PAPHOS, CY	OPTIMUM													1	3	2	2	2	1				
(LAT=34.75N)	AVERAGE											1	3	2	2	2	1						
PERPIGNANT, FR	OPTIMUM															4	2	1	2	2			
(LAT=42.73N)	AVERAGE									2	3	1	2	2	1								
RALEIGH, USA	OPTIMUM										2	1	1	1		1	1	1	1	1	1		
(LAT=35.87N)	AVERAGE					1	2		1	1	1		1	1	1	2							
ROMA, IT	OPTIMUM																4	2	2	2	1		
(LAT=41.90N)	AVERAGE												3	3	1	2	2						
SPLIT, YU	OPTIMUM																6	3	2				
(LAT=43.52N)	AVERAGE												6	2	3								
THESALONIKI, GR	OPTIMUM															3	2	2	2	2			
(LAT=40.33N)	AVERAGE												4	2	2	1	2						
TRIESTE, IT	OPTIMUM																4	3	2	2			
(LAT=45.65N)	AVERAGE												6	2	3								
VALETTA, IT	OPTIMUM														7	4							
(LAT=35.90N)	AVERAGE										2	8	1										
VALENCIA, SP	OPTIMUM														3	3	2	3					
(LAT=39.47N)	AVERAGE											5	2	3	1								
VENEZIA, IT	OPTIMUM															3	3	2	3				
(LAT=45.43N)	AVERAGE										2	3	3	2	1								

cooling season among the four sites, has sky temperature depression values less than 10°C for a significant number of hours.

Figures 2–6 give the mean daily useful cooling energy provided per square meter of radiating surface, for the European locations. For each of the 28 southern European cities (from Table 1), the first row of numbers gives the values obtained for the optimum (clear) sky conditions, while the second row gives the values obtained for the average sky conditions. For each one of these conditions, there are two values. The first column corresponds to the case of an uncovered radiator and the second column to the case of a radiator covered with a wind screen. Each figure presents the results obtained for a typical day of each month in the colling season, May through September. The corresponding results for the 4 southeastern United States cities are given in Table 6.

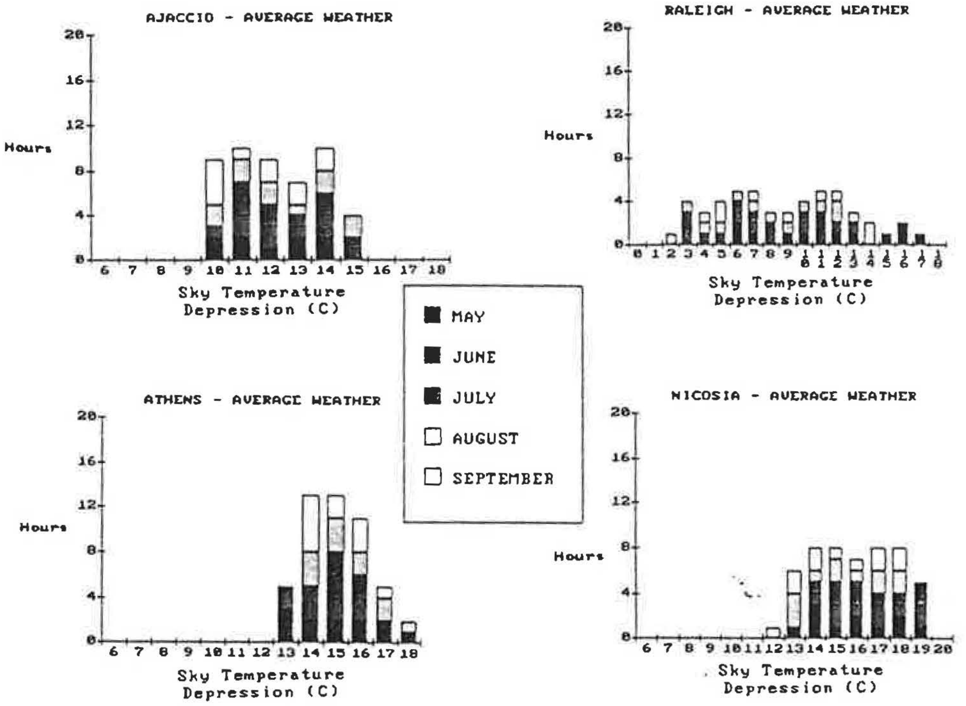

Figure 1 Variation of sky temperature depression at (a) Ajaccio, FR (b) Nicosia, CY (c) Athens, GR (d) Raleigh, NC, U.S.A.

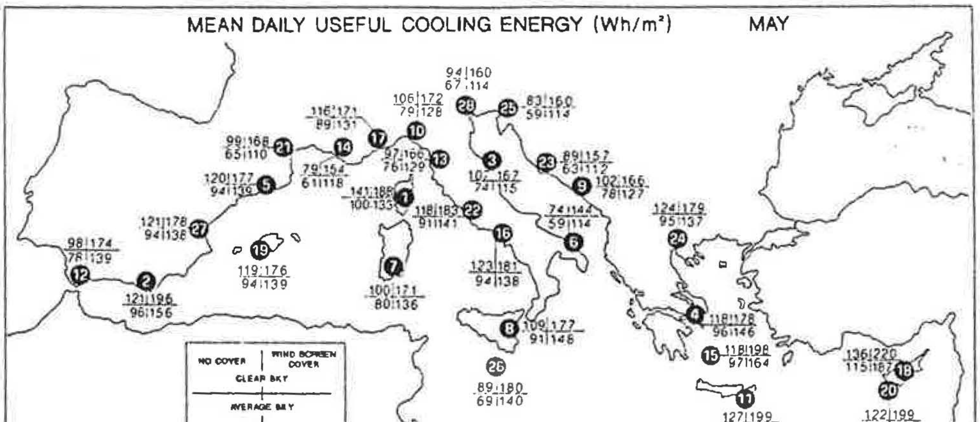

Figure 2 Mean daily useful cooling energy (Wh/m^2) in May for a radiative cooler with a fluid velocity at 2.5 m/sec. Information for each numbered location are given in Table 1.

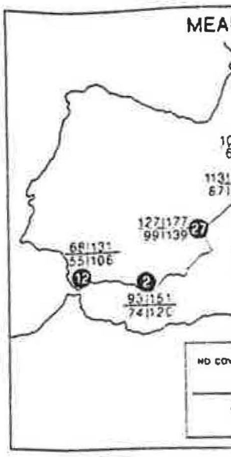

Figure 3 Mean daily u
velocity at 2.5 m/sec. In

The mean daily u
at the various sout
average sky condit
U.S. cities the corr
sky conditions and

The influence of
which are dominat
month of May unde
95% higher than th
hand, at some loc

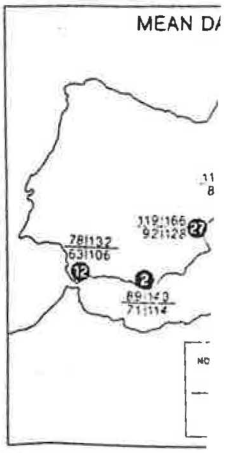

Figure 4 Mean daily
at 2.5 m/sec. Informa

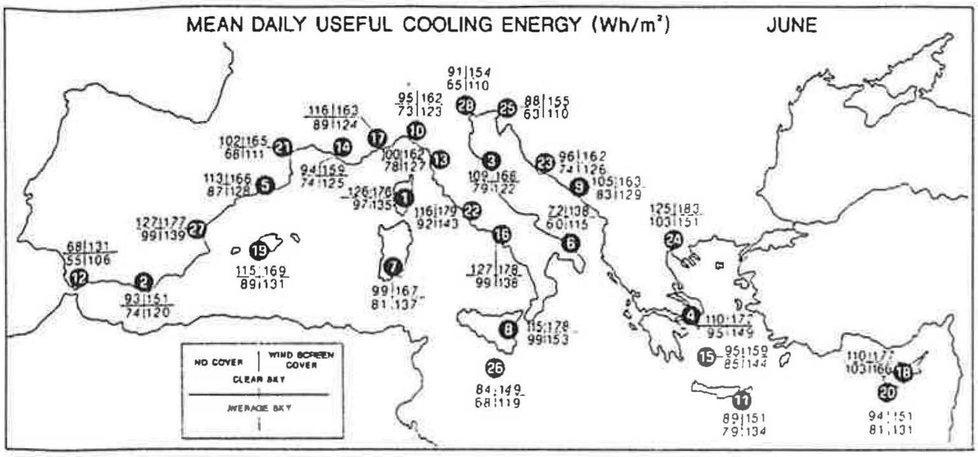

Figure 3 Mean daily useful cooling energy (Wh/m^2) in June for a radiative cooler with a fluid velocity at 2.5 m/sec. Information for each numbered location are given in Table 1.

The mean daily useful cooling energy delivered by the flat plate radiative cooler at the various southern European cities, ranges between 55 and 208 Wh/m^2 for average sky conditions, and 68 to 220 Wh/m^2 for clear sky conditions. For the U.S. cities the corresponding values range between 41 to 136 Wh/m^2 for average sky conditions and 69 to 182 Wh/m^2 for clear sky conditions.

The influence of the wind screen can play an important role at some locations which are dominated by high wind speeds. For example, at Brindisi during the month of May under clear skies, the useful cooling energy of a covered radiator is 95% higher than the corresponding value of the uncovered radiator. On the other hand, at some locations where the wind speed is relatively low, the effect of a

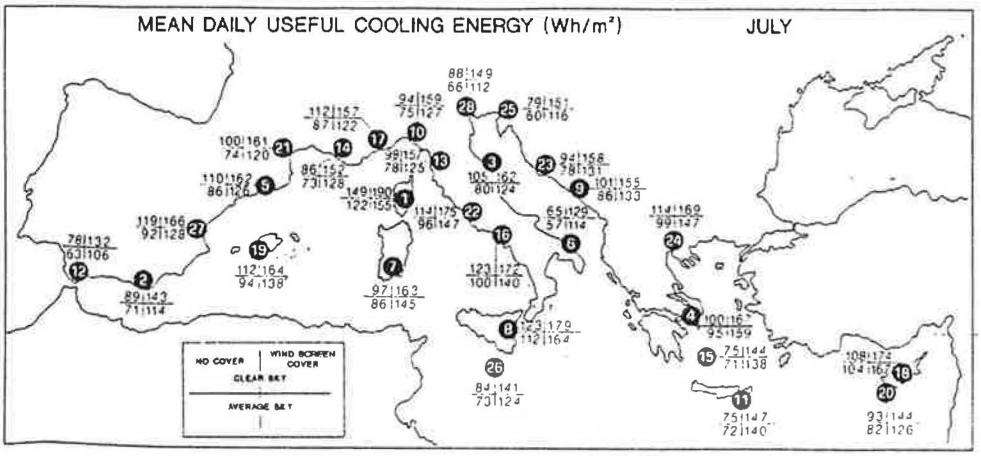

Figure 4 Mean daily useful cooling energy (Wh/m^2) in July for a radiative cooler with a fluid velocity at 2.5 m/sec. Information for each numbered location are given in Table 1.

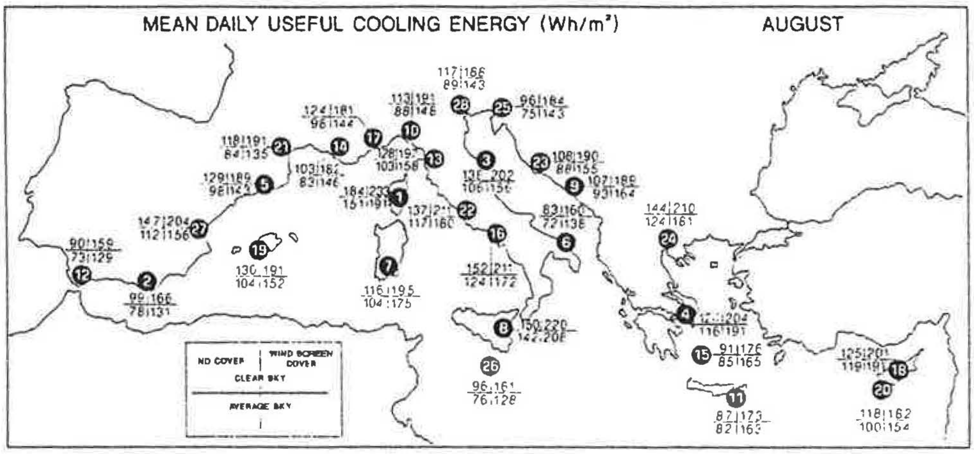

Figure 5 Mean daily useful cooling energy (Wh/m^2) in August for a radiative cooler with a fluid velocity at 2.5 m/sec. Information for each numbered location are given in Table 1.

wind screen is less effective. For example, at Ajaccio the corresponding values differ only by 33%. A similar increase is also observed in August and September at the island of Milos – Greece, located at the Aegean sea. During these months the area is dominated by strong northern winds which influence greatly the performance of the system.

COMPARISON WITH EXPERIMENTAL DATA

Experimental data on the performance of radiative cooling components in southern Europe are very limited. Some results on specific aspects of radiative

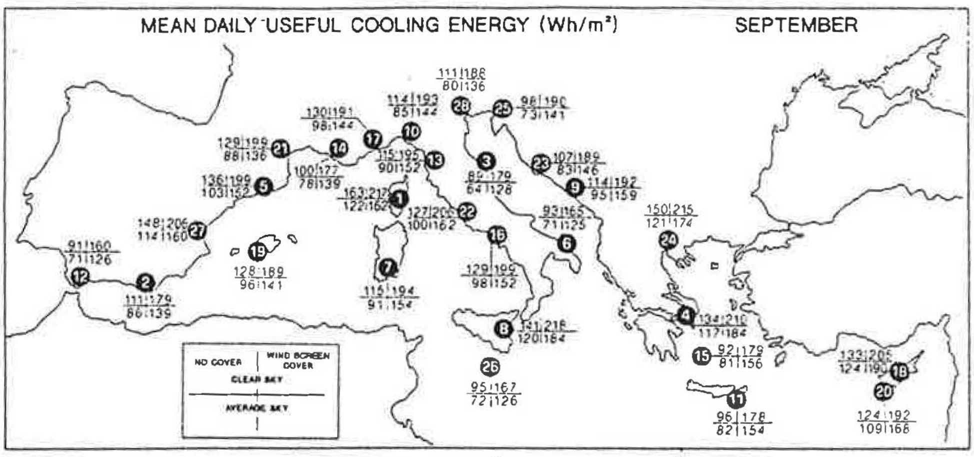

Figure 6 Mean daily useful cooling energy (Wh/m^2) in September for a radiative cooler with a fluid velocity at 2.5 m/sec. Information for each numbered location are given in Table 1.

Table 6. Me

LOCATION
ATLANTA, (
MIAMI, FL
CHARLESTON
RALEIGH, N

cooling have be
perimental data s
A comparison
data in Europe
reported, the ac
verified by Ito a
agreement with e
The present w
cooling potential
researchers and e
in order to exten

CONCLUSIONS

In this paper, th
of a typical fla
southeastern U.S
the effectiveness
Accordingly,
potential for the
cities, it appears
that radiative co

NOMENCLAT

A radiator
C_1 $(C_2 T_{dry})$
C_2 constant
C_3 constant
c_p specific
DT_{sky} sky tem

Table 6. Mean daily useful cooling energy (Wh/m^2) for Southern United States Cities

LOCATION	LAT	SKY CONDITION	COOLING ENERGY (Wh/m^2) NO SCREEN/WIND SCREEN MAY	JUNE	JULY	AUGUST	SEPTEMBER
ATLANTA, GA	33.5 N	Clear	103/182	77/131	75/124	95/155	98/167
		Average	77/136	51/87	45/74	60/99	69/117
MIAMI, FL	25.8 N	Clear	86/147	87/146	88/147	84/143	91/160
		Average	54/101	46/79	48/81	49/82	45/76
CHARLESTON, SC	33 N	Clear	91/160	69/120	83/141	86/143	90/152
		Average	60/107	41/72	45/76	49/81	56/96
RALEIGH, NC	35.9 N	Clear	104/178	81/134	78/127	97/155	103/170
		Average	74/128	54/89	49/79	60/97	72/119

cooling have been reported in the literature.[13–20] However, a complete experimental data set on the performance of metallic radiators is not available.

A comparison of the data used in the present study with available experimental data in Europe has shown a satisfactory agreement. As it was previously reported, the accuracy of the present method has also been experimentally verified by Ito and Miura,[10] while the overall method predicts results in close agreement with experimental data reported for northern American locations.[6]

The present work offers a simple and accurate method to predict the radiative cooling potential in southern Europe and therefore is very useful for building researchers and energy engineers. Further experimental work is necessary though in order to extend our knowledge on the topic.

CONCLUSIONS

In this paper, the sky temperature depression and also the useful cooling energy of a typical flat plate radiative air cooler at 28 southern European and 4 southeastern U.S. cities was calculated. These parameters allow the estimation of the effectiveness and feasibility of radiative cooling applications.

Accordingly, one may conclude that southern Europe exhibits a promising potential for the use of radiative cooling. Compared with the results from the US cities, it appears that the weather conditions of the southeastern states are such that radiative cooling techniques will be of a very low efficiency if applied.

NOMENCLATURE

A	radiator surface
C_1	$(C_2 T_{dry})/(C_3 + T_{dry})$
C_2	constant = 17.08085
C_3	constant = 234.175
c_p	specific heat at constant pressure
DT_{sky}	sky temperature depression

h convective heat transfer coefficient
h_e effective heat transfer coefficient
k_p thermal conductivity of radiator plate
m mass flow rate
n total opaque cloud amount
q_o net radiative power of a blackbody at T_a
q_r net heat flux of nonselective radiator at T_r
q_s sky irradiance
RH relative humidity
t hour of day
T_{ad} adiabatic temperature
T_{dp} dew point temperature
T_{dry} dry bulb ambient temperature
U_p overall heat transfer coefficient
V wind speed

Greek Characters

$\Delta\varepsilon_d$ instantaneous clear sky emissivity
ε_{cs} clear sky emissivity
ε_s cloudy sky emissivity
ε_{sky} sky emissivity
σ Stefan–Boltzmann constant

Subscripts

a ambient
f fluid
i inlet condition
o outlet condition
r radiator
s sky

Refererences

1. T. C. Steemers, *Int. J. Solar Energy*, **10**, 5 (1991).
2. Horizontal Study on Passive Cooling (M. Santamouris Editor, C.E.C. – BUILDING 2000 project, 1990), Chap. 1, pp. 1–7, organized by DG 12, EEC.
3. G. Clark, Proceedings of the International Passive and Hybrid Cooling Conference (A. Bowen, E. Clark, K. Labs editors, Miami Beach, 1981), pp. 682–714.
4. M. Santamouris, Proceedings of Passive Cooling Workshop (E. Aranovich, T. Steemers and O. Fernandes Editors, Ispra, 1990).
5. *Weather in the Mediterranean*, (Her Majesty's Stationery Office, 1964), Vol. II.
6. Climates of the States, Climatography of the United States No. 60-8, No. 60-9, No. 60-31, and No. 60-38, 1975.
7. X. Berger, B. Cubizolles and I. Donet, *Solar & Wind Technology* **5**, 353, (1988).
8. M. Martin, Passive Cooling (J. Cook Editor, M.I.T. Press, 1989), Chap. 4, pp. 138–196.
9. Aspirations – Psychrometer Tafel, Deutscher Wetterdienst, 5, Auflage, Vieweq Verlag, Braunschweig, 1976.
10. S. Ito and N. Miura, *Journal of Solar Energy Engineering*, **111**, 251, (1989).
11. M. Mostrel M. and B. Givoni, *Passive Solar Journal*, **1**, 229, (1982).
12. J. A. Duffie and W. A. Beckman, *Solar Engineering of Thermal Processes* (John Wiley and Sons, New York, 1980).
13. A. Fragoudal
14. A. Addeo, E
Cimento, **1**, 4
15. S. Catalanotti
(1975).
16. S. Golli and
(1981).
17. P. Grenier, F
18. X. Berger, C
19. B. Bartoli, E
Energy, **3**, 26
20. G. Papadakis

13. A. Fragoudakis, G. Papadaki and S. Kyritsis, *Int. J. Solar Energy*, **7**, 73, (1989).
14. A. Addeo, E. Monza, M. Peraldo, B. Bartoli, B. Coluzzi, V. Silvestrini and G. Troise, *Il Nuovo Cimento*, **1**, 419, (1978).
15. S. Catalanotti, V. Cuomo, G. Piro, D. Ruggi, V. Silvestrini and G. Troise, *Solar Energy*, **17**, 83, (1975).
16. S. Golli and Ph. Gremir, *Journal de Physique*, Collogue, Supplement to No. 1, 42, C1 431, (1981).
17. P. Grenier, *Revue de Physique Appliquee*, **14**, 87, (1979).
18. X. Berger, C. Awanou and J. Bathiebo, *Int. J. of Ambient Energy*, **9**, 155, (1988).
19. B. Bartoli, B. Catalomoti, B. Coluzzi, B. Cuomo, V. Silvestrinni and G. Troise, *Applied Energy*, **3**, 267, (1977).
20. G. Papadakis, G. Voulgaris, A. Fragoudakis and S. Kyritsis, *Int. J. Solar Energy*, **6**, 279, (1988).