TOWARD DESIGNING STRATEGIES FOR URBAN HEAT ISLAND MITIGATION BASED ON MULTISCALE FLOW CONSIDERATIONS

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ABSTRACT

Much of the on-going discussion on urban heat island mitigation and proposed measures for cooling is based on case-studies taken at a specific scale and settings; the evaluation of the effectiveness of proposed cooling measures is therefore made using performance criteria derived for that specific scenario. The transferability of this knowledge to other sites and climatologies is not ensured. This is because the phenomena dictating the urban climate are inherently multi-scale and the contribution of heating sources or cooling mechanisms as well as their interaction with other ongoing-possibly physical phenomena can be different. Therefore, strategies for urban cooling in a city should consider the mutli-scale nature of urban climate, based on which mitigation actions and costs must be considered. In this work we report results from a multi-scale field experiment conducted in Nicosia-Cyprus in July 2010 to investigate the Urban Heat Island (UHI) in Nicosia capital city and its interaction with multi-scale meteorological phenomena that take place in a broader region over Cyprus. Specifically, the results are analysed and interpreted in terms of a non-dimensional/scaling parameter dictating the urban heat island circulation reported from laboratory experiments (Fernando, 2010). We find that the field measurements obey the same scaling law during the day, in the absence of any other flow phenomena apart from the urban heating. During the night we find that the deduced non-dimensional value reduces to half (compared to that during the day); this is due to the presence of katabatic winds from Troodos mountains into the urban center of Nicosia and their cooling effect superimposed on diurnal urban heating. Based on this deduction, we evaluate the impact of various proposed heat island mitigation measures in urban planning.

KEYWORDS

Field experiments, urban meteorology, mediterranean urban climate

1 INTRODUCTION

Urbanization has been increasing at an alarming rate: while in the 1800's, only 3% of the world's population lived in urban areas, by the 1950's the urban population increased to 30% and in 2000 it reached 47%. With this ever increasing growth, numerous issues have been raised, such as air quality issues, sustainable use of energy, maintenance of waste materials and socio-economic status of urban inhabitants as well as on the presence of the urban heat island phenomenon [6]. Much of the on-going discussion on urban heat island mitigation and proposed measures for cooling is based on case-studies taken at a specific scale and settings; the evaluation of the effectiveness of proposed cooling measures is therefore made using performance criteria derived for that specific scenario. The transferability of this knowledge to other sites and climatologies is not ensured. This is because the phenomena dictating the urban climate are inherently multi-scale and the contribution of heating sources or cooling mechanisms as well as their interaction with other ongoing-possibly physical phenomena can be different. Therefore, strategies for urban cooling in a city should consider the mutli-scale nature of urban climate, based on which mitigation actions and costs must be considered. In this work we report results from a multi-scale field experiment conducted in Nicosia-Cyprus in July 2010 to investigate the Urban Heat Island (UHI) in Nicosia capital city and its interaction with multi-scale meteorological phenomena that take place in a broader region over Cyprus. Specifically, the results are analysed and interpreted in terms of a non-dimensional/scaling parameter dictating the urban heat island circulation reported from laboratory experiments (Fernando, 2010). Therefore strategic urban design decisions for UHI mitigation should take into account any scaling laws that bound the behaviour of the built environment in order to develop measures that would mitigate UHI.

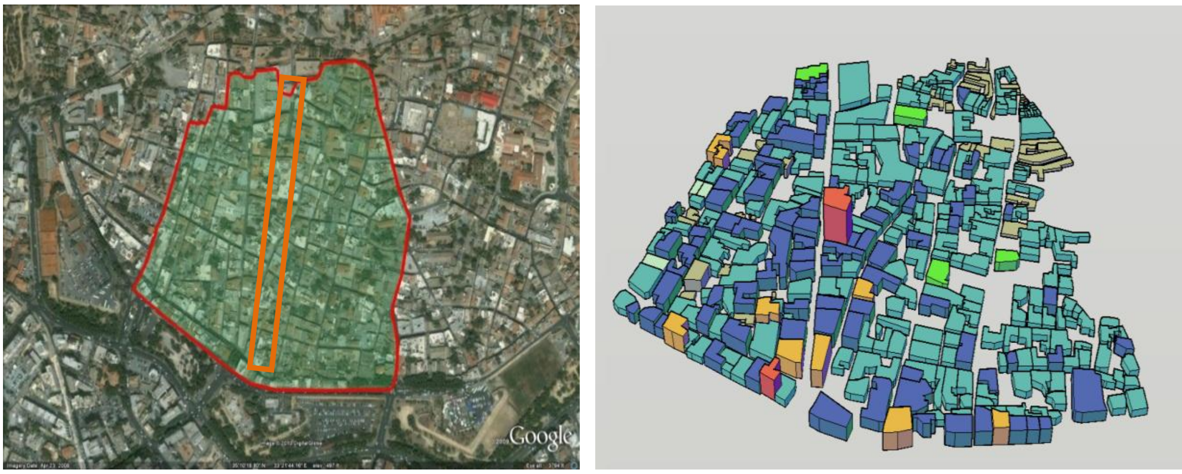


Figure 1: The investigated Nicosia's old city centre encircled with the red continuous line (on the Right-Hand-Side); the orange line encircles the steet (Ledras Street) under investigation. On the Right-Hand_Side, the AUTOCAD model mapping of the region is shown taking account coloured according to the building height of each building volume.

2 METHODOLOGY

2.1 Field Site

In terms of the site selection, the parameters of building height, building density and paved and unpaved area coverage were examined. This analysis provided fundamental data for all the subsequent tasks and actions. The objective was to create a complete database of the investigated area in order to assess the status of urban environment in Cyprus. Hence, major groups of building blocks (approximately 350 building blocks) were analyzed and scaled down for the applied channel, in order to support the parameterization studies for the investigated scenarios. Within this task, the geometries under investigation were also be modelled for the purposes of the CFD study. The building energy behaviour and performance are heavily influenced by the density of the building space that is why the facades chosen have different SVF. For example facades that are placed in front of an open parking area (H/W<1) can be compared with some others that are placed in a canyon. Some other important factors were the orientation of the chosen facades and the properties of the surrounding surfaces in the same canyon.

Among the investigated neighbourhoods, the old city centre of Nicosia appeared as being the most representative for the Mediterranean-like architecture, therefore it was decided that the field campaign should be carried out in this area (see Fig. 1). The old town centre, which is the historical centre of the city, is delimited by Venetian type walls. It is generally characterized by narrow canyons with Mediterranean-style planning but also includes some buildings of contemporary architecture and also some large squares. From the West to East, four major sub-neighbourhoods (SN) could be identified according to homogeneity and packing building density SN1 to SN4. SN1 includes some larger open spaces/parking lots so that it has an overall lower packing density and it is less homogeneous. SN2 is homogeneous over relatively large distances in neighbourhoods units. SN3 has some broader avenues and squares so that it has a lower packing density. SN4 has a very large packing density being also relatively uniform.

2.2 Intensive observation periods

During the field measurement campaign, different types of measurements were taken. As the collected data are too many and complex, Table 1 summarizes briefly the collected data of the field campaign measurements. The period of the campaign is divided in three periods. The intensive observation period, 01-20/07/2010 where meteorological data are collected from different scales, the intensive observation period 10-12/07/2010, where with meteorological data buildings' temperature and humidity are collected and the peak day 12/07/2010 where radiosoundings and aerial thermography took place. Additionally, a supplementary investigation about the influence of the trees of the street temperature took place during 14-16/07/2010.

2.2.1 Meteorology across the scales – measurement procedure

2.2.1.1 Synoptic Scale

Meteorology at the synoptic scale was recorded during the observation period from 7th to 15th July 2010 using a radiosounding system. It is noted that the radiosounds were released from Nicosia old city centre area at (33.3613˚ E, 35.1741˚ N), in order to capture the urban profile characteristics of the lower layers. The sounding system provided measurements of the air pressure, temperature and humidity as well as of the wind speed and direction in corresponding altitudes. Sets of the measured data were sent down to a receiving station (ground station) as the radiosond was carried aloft by a balloon. For the days of the 7th , 10th , 11th and 15th of July 2010, the radiosoundings were released at a sporadic rate, while for the observation day of the 12th July 2010, radiosounds were released every three hours, in order capture the profile variation throughout the day.

2.2.1.2 Regional Scale

In order to examine the phenomenon of UHI in the city of Nicosia, meteorological data from Cyprus Meteorological Service for Nicosia and its surroundings are collected. Because of the Turkish occupation on the northern part of the island, meteorological data from this direction were not available. The five stations from where data were collected and analyzed from Nicosia broader surroundings are Nicosia_PASYDY, Athalassa, Athienou, Astromeritis and

Table 1: List of TOPEUM collected data according to the scale of observation, both for Meteorology and Building

Surface Temperature Respond; starting from the data of the observation period 01-20 of July 2010, moving to the data of intensive observation period 10-12 of July 2010 and ending with the data of the peak day 12th of July 2010.

Category	Scale	Collected Data	Stations	Data Time Interval	Data Origin
Meteorology	**Regional Scale**	Meteorological Data: WS and WD (10m Height), T (2m Height)	*Nicosia_Pasydy* *Athalassa* *Tamasos* *Athienou* *Astromeritis*	Hourly	Cyprus Meteorological Service
Meteorology	**Local Scale**	WS, WD, T patterns	*Sonic 1* (Ariadnis str. _ 5m height) *Sonic 2* (Rooftop in Ledras str. _ 5m height from rooftops, 26.8m from the ground) *Sonic 3* (Ledras str. _ 5m height) *Sonic 4* (Arsinois str. _ 5m height)	Hourly	TOPEUM Field Experiment
Meteorology	**Synoptic Scale**	Meteorological Maps (500hPa and surface)		00UTC and 12UTC	Cyprus Meteorological Service
Building Surface Temperature Response	**Neighborhood Scale**	On ground thermography	*Building 1* Exhibition Hall-Municipality of Nicosia, Ledras str. *Building 2* CYTA, Arsinois and Onasagorou str. *Building 3* Church, Solonos str. *Building 4* Onasagorou str. *Building 5* Fokionos str.	Every 2 hours	TOPEUM Field Experiment
Building Surface Temperature Response	**Building Scale**	Termocouples in 4 levels a) ground level b) 0,40m height c) 1,20m height d) 2,00m height	*Building 1* Exhibition Hall-Municipality of Nicosia, Ledras str. *Building 2* CYTA, Arsinois and Onasagorou str. *Building 6* Ledras str.	Every 10 minutes	TOPEUM Field Experiment
		in situ temperature and relative humidity measurements	*Building 1* Exhibition Hall-Municipality of Nicosia, Ledras str. *Building 2* CYTA, Arsinois and Onasagorou str. *Building 6* Ledras str.	Every 6 hours	TOPEUM Field Experiment
Meteorology	**Synoptic Scale**	Radiosoundings	*Theatre of Bank of Cyprus Cultural Foundation* Faneromenhs str.	Every 3 hours	TOPEUM Field Experiment
Building Surface Temperature Response	**Urban Scale**	Aerial thermography		Morning: 8am	TOPEUM Field Experiment
			Old City Centre	Afternoon: 3pm	
				Night: 10 pm	
Meteorology	**Synoptic Scale**	Radiosoundings	*Theatre of Bank of Cyprus Cultural Foundation* Faneromenhs str.	**7 of July 2010**_07:30 and 11:30pm **11 of July 2010**_1:30pm **15 of July 2010**_02:30 and 11:30 pm	TOPEUM Field Experiment
Building Surface Temperature Response	**Building Scale with trees influence**	Thermocouples in 3 levels on two different walls (east and west) of each building a) 2m height b) 3m height c) 4m height	*Building 7* Flo Café (with trees) *Building 8* Toy store (without trees)	**14-16 of July 2010** Every 10 minutes	TOPEUM Field Experiment

Tamasos for the period from the 1st to the 20th July 2010. Information on the surrounding wind directions as well as wind speeds was recorded at a height of 10m above the ground in the corresponding areas. It is noted however, that the anemometer of the Nicosia-PASYDY station is placed at a height of 2m, in the vicinity of buildings, hence comparisons of wind data from this station was avoided.

2.2.1.3 Urban and Local Scale

The smallest scale analyzed is the local scale. For the investigation of the wind direction, wind speed and wind temperature, four places in Ledras Street neighborhood are examined during the period from the 7th to 20th July 2010. A sonic anemometer (denoted as Sonic 2 in figures), was placed at the rooftop of the University of Cyprus Architecture School in Ledras Street, which is the second highest building of the region, in order to capture the meteorology of the urban scale. Another sonic was placed on School of Architecture building in the street canyon, in Ariadnis street (denoted as Sonic 1). In addition, a sonic was placed in Ledras Street (denoted as Sonic 3), and another one in the perpendicular street to Ledras Street, Arsinois street (denoted as Sonic 4).

2.2.2 Building surface Temperature response – measurement procedure

2.2.2.1 Urban Scale

In order to capture the impact at the urban scale of the solar radiation exposure of the built environment, aerial thermography took place during the morning, afternoon and night of 12th July 2010, above the historical centre of Nicosia, which is also the geometrical centre of the city. The three different times of the day, in which aerial thermography took place were chosen in order to capture buildings' thermal response. Hence, as during the observation period, sun rise was at about 5:40-6:00 the morning aerial thermography took place at 8:00, two hours after sunrise in order to allow enough time for the building thermal response. In a similar way afternoon aerial thermography took place at 15:00, two hours after the corresponding solar zenith at the intensive observation period. Finally, aerial thermography took also place at night 22:00, about three four hours after the sunset, during which city's activities minimized. It is noted that during the aerial thermography, there were important restrictions; due to the Turkish-occupied part of central Nicosia and the restricted activities allowed by the Turkish occupying army, aerial thermography could not take place from a distance closer than 1km south of United Nations buffer zone. Hence infrared images were taken under an angle of about 45˚. Additionally, the minimum height in which helicopter could fly was about 400m from the ground. In order to verify the quality of the infra-red images captured by the thermocamera, a verification thermocouple measurement was simultaneously conducted from a public school rooftop (Archibishop Makarios Lyceum, Nicosia), recording the corresponding temperature, and at the same time an infrared image of the rooftop from the thermocamera at angle of 45˚ and height of 400m was captured. Temperatures recorded with the thermocouple and the infra-red thermocamera differed by 7% providing an acceptable accuracy.

2.2.2.2 Neighborhood Scale

Moreover, five buildings, made of similar materials, are chosen in the broader neighborhood of Ledras Street in order to the record the thermal response of several materials during different times of the day for the intensive observation period 10th to 12th July 2012. Infra-red images were taken approximately every two hours during the three-day intensive observation period, following a circuit path between the five different buildings. Buildings' selection criteria included their orientation, the street canyon height-to-width ratio and the material of the façade.

2.2.2.3 Building Scale

At the local-building scale, the surface temperature and humidity over a building wall were recorded during the three-day intensive observation period at different times of the day. Specifically measurements were taken locally at four different elevation points over each building wall (of the different buildings), ranging from ground level up to 2.00 m heigh.

3 RESULTS

3.1 Summarised results: multi-scale meteorology and urban building thermal response

Multiscale meteorological measurements and simulations were recorded. Figure 2 shows simulation results from different resolutions for the background wind fields at different resolutions. Figure 3 shows the results from the radiosoundings tracking and processing; this enables the estimation of the boundary layer height. Radiosoundings indicate the structure of the atmosphere depending on the vertical height. Several radiosondes were released in the period 7th -15th July 2010. Radiosoundings on 7th, 11th and 15th of July were diagnostic, while during the peak observation period, on the 12th of July, one radiosonde was released every three hours creating the vertical profile of the atmosphere during the day. The position of each radiosound during the recording period is illustrated in Figure 3. Radiosounding results showed that the troposphere height in Cyprus is slightly higher than its nominal height of 11 km. According to radiosounding profiles for potential temperature, the height of inversion layer was deduced to be approximately 17km, corresponding to the troposphere height in Cyprus.

Supplementary information on weather conditions during the days of IOP was obtained using the Weather and Research Forecasting (WRF) model - version 3.4, which was run at the Cyprus Institute High Performance Computing. WRF is a state-of-the-art mesoscale model designed to serve both operational forecasting and atmospheric research needs (Skamarock et al., 2007). To drive the model, the NCEP FNL (Final) Operational Global Analysis data of 1.0 x 1.0 degree resolution updated every six hours (http://rda.ucar.edu/) is used; this product is from the Global Data Assimilation System (GDAS), which continuously collects observational data. In relation to the topography, during 22:00-03:00 katabatic winds from Troodos mountain take place, and start to get disorganized at 04:00 to 05:00 in the morning, as sun rises. At 06:00 in the morning, as the heating of the ground surface begins, anabatic winds appear and are observed until 15:00. At the same time such an activity is not observed for Pentadaktulos mountain. Moreover, at 06:00 in the morning eastern winds are observed in Nicosia and Athienou and these speeds are increased at 08:00 and become SE. At the same time SW winds are observed in Astromeritis due to sea breezes and then get strengthened at 11:00. In the noon, 13:00-14:00, the two flows, are merged indicating tunnel phenomenon in Nicosia, which disappear at 15:00-16:00. Finally, from 17:00 until the first hours in the morning, west winds are observed northern of Troodos Mountain, with speeds which are continuously decreasing until 19:00 to 3m/s and then increased to approximately 6m/s until 03:00.

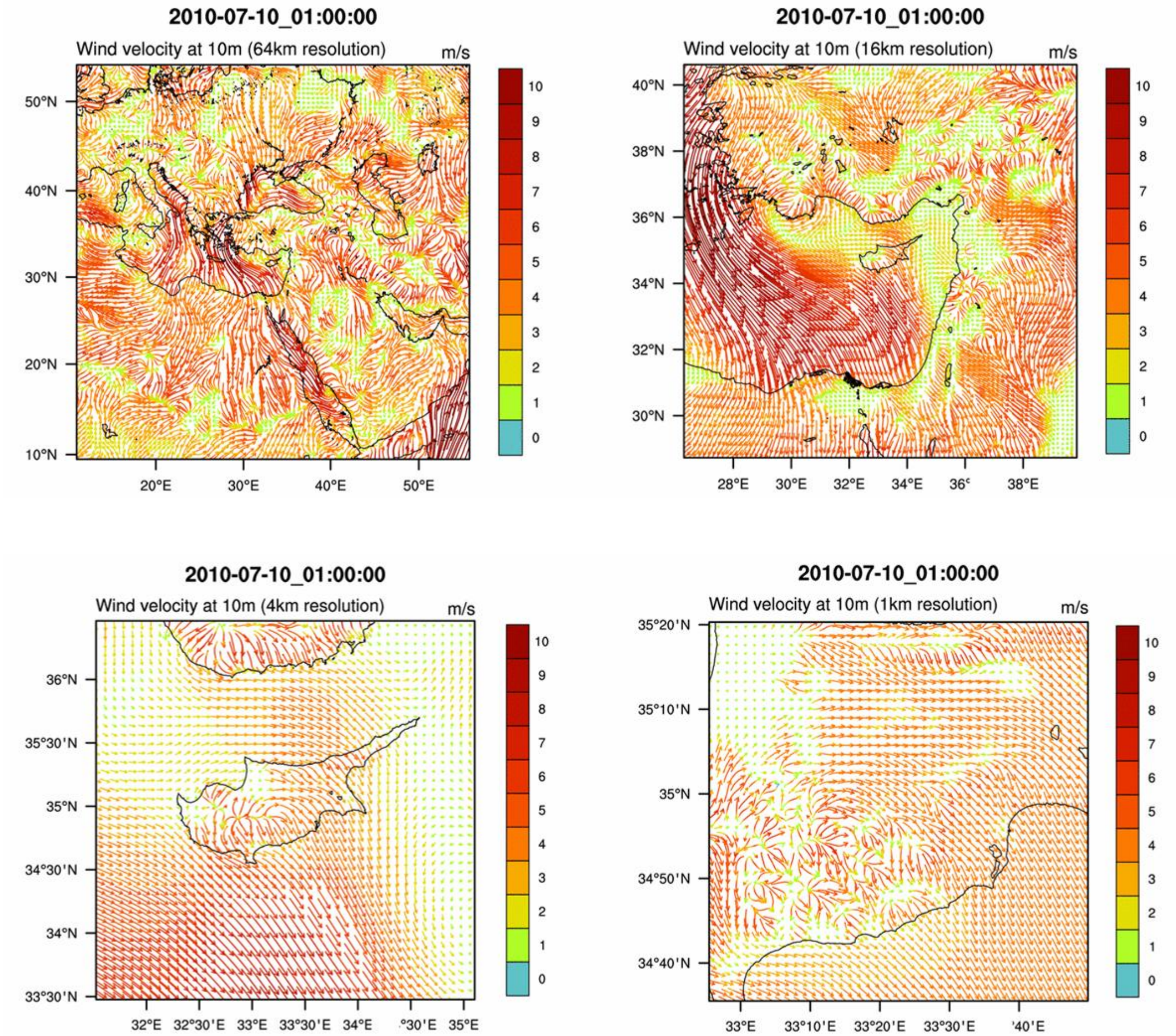


Figure 2: Wind flow in the region of Cyprus, from WRF model results (Produced by Georgios Zittis – Cyprus Institute, 2012). Video provided in the appended cd.

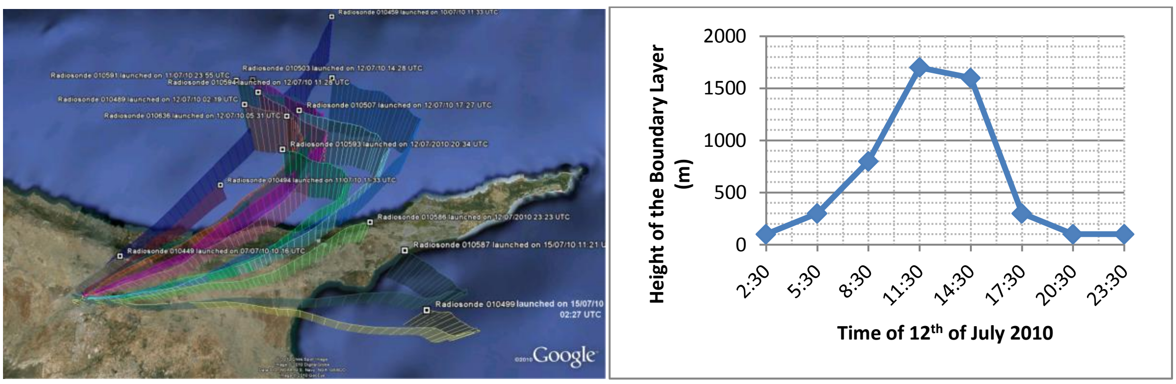


Figure 3: Radiosoundings traces during the intensive observation period (left); the evolution of the height of the atmospheric boundary layer during 12th of July 2010 (right)

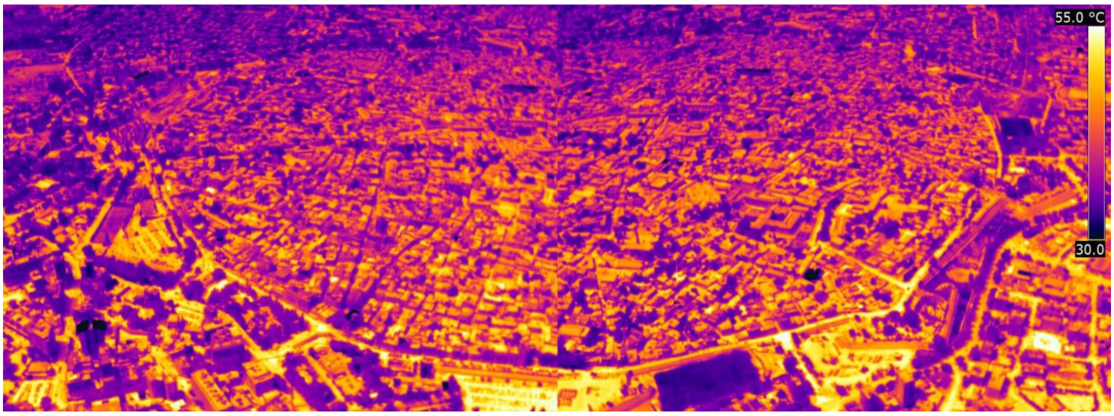


Figure 3: Aerial infrared image during the afternoon, of 12th July 2010 at 3pm.

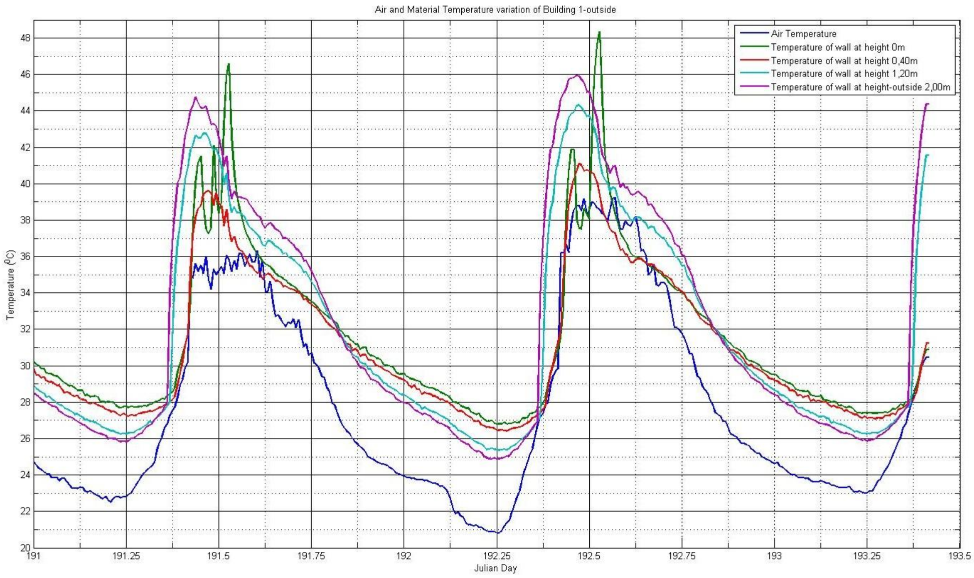
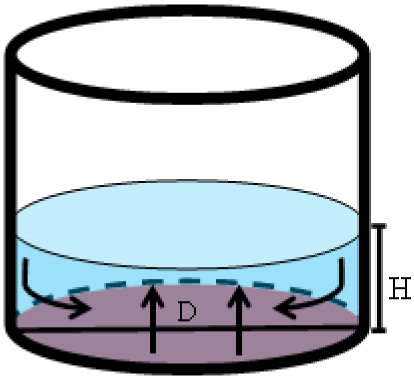


Figure 4: Air temperature variation in comparison with material temperature variation recorded from the thermocouples outdoor of Building 1, Ledras street.

3.2 Analysis and interpretation of the observed Urban Heat Island

Meteorological conditions across various scales were monitored in order to account appropriately for the influence of such phenomena possibly contributing to the Urban Heat Island (UHI) phenomenon. Urban area data were taken from those recorded at Nicosia-PASYDY station while rural area data were taken from Astromeritis and Athienou: Astromeritis is closer to the sea-coast than Athienou, and as observed from WRF simulations it is mainly affected by sea breezes, hence cooling effects are taking place.

The magnitude of a UHI is defined as the temperature difference between urban and rural areas, ΔT_{U-R}. No standard protocol exists on measurement stations used for ΔT_{U-R}. During the day, air temperatures of Nicosia- PASYDY are greater than the temperature in Athienou by $\Delta T_{U-R} = 0.5 - 3.5\,^{\circ}C$. However during the night the temperature difference is not as large as during the day. The nocturnal temperature difference varies from $\Delta T_{U-R} = 0.5 - 1.5$ °C. The results show that the existence of UHI is provident, although its magnitude is not as large as compared to other south-european studies eg in Athens (Kolokotsa et al, 2000).



Laboratory experiments conducted by Fernando et al. (Fernando et al, 2010), considered the city as a circular source of heat taking into account the convergence flow that arises as a result of the thermal flows due to the UHI phenomenon. A dimensionless parameter, independent from Reynolds number, was proposed. In the experiments, the bottom of the tank was a heated disk, of diameter D, in a stably stratified fluid; the results show that for a uniform heat flux Q_0 (or a buoyancy flux $q_0 = gaQ_0 \quad \rho_0 c_p$) the resulting ground level convergence velocity U_r (of buoyancy frequency N) is given by $U_r \approx 0.7(q_0 D)^{1/3}$, and when the temperature difference between the disk and ambient fluid ΔT_{U-R} is specified, then $U_r \quad ga\Delta T_{U-R} D \quad ^{1/2} = 0.08 \pm 0.01$.

For the calculation of this dimensionless parameter, data from Architecture Rooftop - Sonic 2 as representative of the heated urban area urban area are taken into account, as the data of this height approaches better the heated disk. Data from street, Sonics 1, 3 and 4 have not been considered as most suitable for the β-parameter calculation as the conditions in the canyons, are affected also by shading, trees etc. During the day, due to the fact that sea breezes from Astromeritis reach Nicosia, Athienou is considered as rural area in our analysis. Consequently, the dimensionless parameter as deducted from our field experiments (for diurnal variations) is $\beta = 0.0789$, approximately equal with the idealized laboratory value 0.08 ± 0.01. This indicates the existence of UHI during the day in Nicosia, which is in agreement with the high temperature difference between Nicosia-PASYDY and Athienou.

During the night, katabatic winds from Tamasos affect Nicosia. In the nocturnal case, the non-dimensional β parameter is found to be 0.0346, approximately half compared of the value during the day and the laboratory value. Again this lower value indicates the lower magnitude of UHI during the night, as temperature difference form Nicosia-PASYDY and Athienou shows. Despite the small value of β, it could be said that UHI also exists during the night, at a lower intensity, of 50% of the value reported in laboratory experiments. This difference is due to the contribution of katabatic winds.

4 CONCLUSIONS

A multiscale consideration of the urban heat island phenomenon has proven necessary as manifested through a field measurement campaign taken place in Nicosia-Cyprus during July 2010. It was shown with regard to the meteorology that during the summer, Cyprus is characterized by the etesian winds from Westerly to Northwesterly directions, high stability and small variations of atmospheric pressure. At the same time topography has a special role in the air circulation. Coastal regions are mainly affected by sea and land breezes, whereas anabatic and katabatic winds from mountain enhance the development of local wind systems, specifically anabatic and katabatic winds are observed to originate from Troodos Mountain.

Athalassa, which is a suburban area, has greater temperature values and night that urban Nicosia, both during the day, as NW winds are dominant, particularly during the day, and warm air from Nicosia is advected to Athalassa. Athienou is considered as the rural station to Nicosia, as this region is not affected from sea breezes as much as Astromeritis does, not only because is farther away from the sea than Astromeritis is, but also because the effect of the sea breezes are nearly cancelling out with the etesian winds and hence any cooling effect is not enhanced. Furthermore Athienou is closer to Nicosia than Astromeritis, which provides better comparison conditions. Moving closer to the urban area, air temperature variations are observed to be the same both for the height of rooftop and the street canyons conditions. Wind speeds in street canyons are much lower than wind speeds at rooftop level. Furthermore, wind directions in the street canyon are completely different compared to the rooftop level, however wind directions appear to be the same both during day and night in different street canyons even though the canyons may be perpendicular to each other.

Finally, UHI phenomenon is present in the city of Nicosia, with higher magnitude during the day than during the night due to the effect of katabatic winds, specifically the temperature difference between urban and rural area, $\Delta T_{U-R_{day}}$ ranges $0.5-3.5\ ^{\circ}C$ while during night ranges in $0.5-1.5\ ^{\circ}\mathrm{C}$. Moreover, calculation of the scaling dimensionless parameter β during the day is found to be 0.0789 while during the night is 0.0346; this compares quite well with values obtained in laboratory measurements where $\beta = 0.08 \pm 0{,}01$ not indicating other effects such as katabatic cooling.

5 ACKNOWLEDGEMENTS

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