Meteorologische Zeitschrift, Vol. **20**, No. 5, 553-564 (October 2011)

Article

The influence of the summer sea breeze on thermal comfort in Funchal (Madeira). A contribution to tourism and urban planning.

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(Manuscript received October 29, 2010; in revised form September 20, 2011; accepted October 6, 2011)

Abstract

Tourism plays a crucial role for the development of coastal areas. Despite the mildness of Madeira's climate, very hot days can occur during summer, a situation to which most tourists from northern Europe (the majority of foreign tourists) are poorly adapted. As sea breezes strongly contribute to moderate heat stress in urban environments, their influence on the thermal comfort on the island has been studied. Sea breezes occurred on 84 % of the days during the period under study (May to October 2006). They usually start around 09:30 h and end after 22:00 h, with an average duration of about 12:50 hours and a mean velocity of 2.9 m/s. Physiologically Equivalent Temperature (PET) was used to evaluate the thermal comfort of a sample of days during the summer of 2006. It was concluded that most of the sites in the city are "slightly comfortable" during normal days with sea breeze, but only shore sites and the highest green areas offer some comfort during hot days. Inside the city, the thermal perception is generally "hot" and strong heat stress can occur. As sea breezes are important to mitigate heat stress, some basic guidelines were presented: urban planners should take advantage of this wind system avoiding dense construction near the shoreline that would act as a barrier to the renewal of the air inside the city. In terms of tourism, planners and local authorities should provide solutions to mitigate the negative effects during hot periods, creating a system to warn and relocate more vulnerable tourists to places near the shore line, to the mountains, to gardens and air-conditioned buildings. In combination with other components (beauty of the island, gastronomy, cultural values and safety), climate information can be a factor of attractiveness to tourists.

Zusammenfassung

Der Tourismus spielt bei der Entwicklung von Küstengebieten eine wichtige Rolle. Trotz des milden Klimas von Madeira können im Sommer sehr heiße Tage auftreten und die meisten Touristen aus Nordeuropa sind an diese Situation wenig angepasst. Da der Seewind einen wichtigen Beitrag zur Minderung von Hitzestress in urbanen Gebieten leistet, wurde sein Einfluss auf den thermischen Komfort von Menschen untersucht. Während des Untersuchungszeitraums (Mai bis Oktober 2006) wurde der Seewind an 84 % der Tage festgestellt. Er beginnt normalerweise nach 9:30 Uhr und dauert an bis ca. 22:00 Uhr mit einer durchschnittlichen Dauer von 12:50 Stunden und einer Windgeschwindigkeit von 2.9 m/s. Die Physiologisch Äquivalente Temperatur (PET) wurde zur Bestimmung des thermischen Komforts für den Sommer 2006 berechnet. Die Schwellenwerte des Zivilschutzes wurden für die Identifikation von Hitzeperioden verwendet. Es wurde festgestellt, dass die meisten Messtandorte der Stadt leichten Hitzestress bei normalen Tagen mit Seewind und nur Küstengebiete und Grünflächen thermisch komfortable Bedingungen aufweisen. Im inneren Bereich der Stadt wird die thermische Situation generell als "heiß" wahrgenommen, und sehr starker Hitzestress kann entstehen. Aufgrund der Tatsache, dass der Seewind wichtig für die Minderung von Hitzestress ist, wurden Richtlinien aufgestellt: Stadtplaner sollten die Vorteile des Seewindes nutzen und dichte Bebauung im Bereich der Küste vermeiden, weil diese wie eine Barriere die Erneuerung des Luftaustausches in der Stadt behindert. Für die Belange des Tourismus sollten die Planer und lokale Behörden Möglichkeiten zur Abmilderung von negativen Effekten während heißen Perioden bereitstellen, indem sie ein System entwickeln, um gefährdete Touristen zu warnen und in Bereiche nahe der Küsten, in die Bergregionen, in Gärten oder klimatisierte Gebäude zu verbringen. In Kombination mit anderen Faktoren (Schönheit der Insel, Gastronomie, Kulturwerte und Sicherheit), können Klimainformationen einen wichtigen Faktor für die Attraktivität der Insel bilden.

1 Introduction

According to the principles of sustainable development of the European Spatial Development Perspective, Portugal has selected the Atlantic Ocean, the coastal areas and the Atlantic islands as areas with a maritime strategic dimension for the future. These are not only areas of great biodiversity, numerous habitats and species, important natural resources, but also areas of great vulnerability and complexity. In the Portuguese National Programme for Spatial Planning Policy (PNPOT), tourism is the most important activity for local and national de-

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0941-2948/2011/0248 $ 5.40
DOI 10.1127/0941-2948/2011/0248

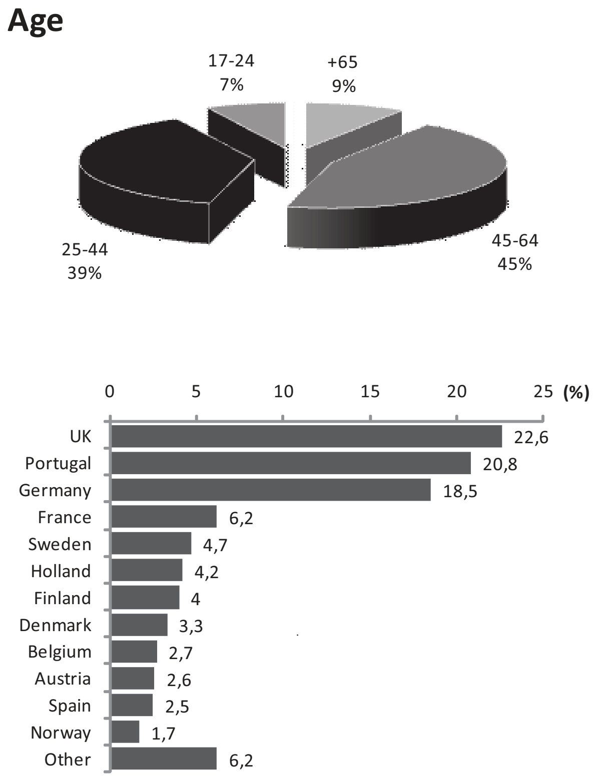

Figure 2: Tourist profile in Madeira Island in 2009.

velopment and therefore it plays a crucial role for the development of these areas (MAOTDR, 2007).

1.1 Study area

Madeira (32°38' N and 16°55' W) is a mountainous Atlantic island (Pico do Areeiro: 1816 m and Pico Ruivo: 1862 m), 660 km away from North Africa and 980 km from Lisbon. A large percentage (43 %) of its population (262 456 inhabitants within the 2011 census) is concentrated in the city of Funchal, located on the southern slope (Fig. 1).

The local economy focuses on the tourism activity of the two islands (Madeira and Porto Santo). In 2009 the archipelago received 1 058 410 guests that spent at least one night in hotels. This corresponds to an income of over 255 Million Euro in that year (INE-Instituto Nacional de Estatística, www.ine.pt). The region has recently been classified as an excellent travel destination by the CED (World Centre of Excellence for Destinations). The profile of the visitors to Madeira during the last years is that of a senior tourism: the majority of the travellers come from northern Europe and continental Portugal, most of them (54 %) are over 45 years and 9 % over 65 years (Fig. 2).

1.2 Madeira's climate

Madeira is an excellent tourism destination, amongst other reasons, due to its mild climate. As far back as in the 18th century, physicians from several European countries recommended its climate to help healing pulmonary diseases and other disorders (Meneses and Silva, 1946). Madeira has a "Mediterranean" type climate, with dry summers and precipitation occurring mainly in autumn and winter. The annual precipitation in the Funchal Region is less than 600 mm, but this value rises to 2900 mm in the highest places of the island (Pico do Areeiro). In the period from 1961–1990, the average temperature varied between 8°C in the highest mountain peaks and 18–19°C in the coastal areas. In fact, the highest temperatures occur on the southern slopes, where the region of Funchal is located. In the wintertime (DJF), the average minimum temperature varies between 4°C (Pico do Areeiro) and 13°C in the coastal areas. In summer (JJA), the observed maximum average temperature is 16°C in Pico do Areeiro and 23°C in Funchal (Santos and Aguiar, 2006). In conclusion, the proximity to the Atlantic, the mountains, the laurissilva forest, and the compact city of Funchal give rise to a great variety of local climates (Lopes, 2007).

Despite the mildness of its climate, very hot summer days may occur. In a study about the "Natural and Anthropogenic Hazards in Funchal" (CMF, 2011), several climatic risks were assessed. The authors considered the "yellow warning" criteria used by the Portuguese Health Ministry and the National Authority for Civil Protection to assess heat waves: maximum temperature $\geq$ 32°C and minimum temperature $\geq$ 24°C. Over the past 50 years, one short episode of very hot weather occurred on average every five years between May and October in the Funchal region.

Heat waves increase thermal stress and induce health problems especially for elderly and sensitive individuals (a large percentage of Madeira's tourists). In the worse scenarios, heat waves can be the cause of mortality amongst the more vulnerable individuals with chronic obstructive pulmonary disease and respiratory tract infections (Ayres et al., 2009). According to the IPCC A2 scenario, by the end of the 21st century the warm season will be longer and an increase of 15 % of hot days with extreme thermal stress is expected in Madeira (Casimiro and Lourenço, 2006).

Sea breezes can bring benefits to urban coastal areas, by causing a strong reduction of air temperature (Alcoforado et al., 2009; Papanastasiou et al., 2010). Therefore, these systems play an important role in the improvement of urban environments and more so in the near future, due to the projected temperature increase. However, only a few studies (Lopes, 2007; Lopes et al., 2010) have looked into these systems and their interaction with human activities on Madeira Island.

1.3 Objectives and need of this study

Climate is a major concern when choosing travel destinations (de Freitas, 2003; Lin and Matzarakis,

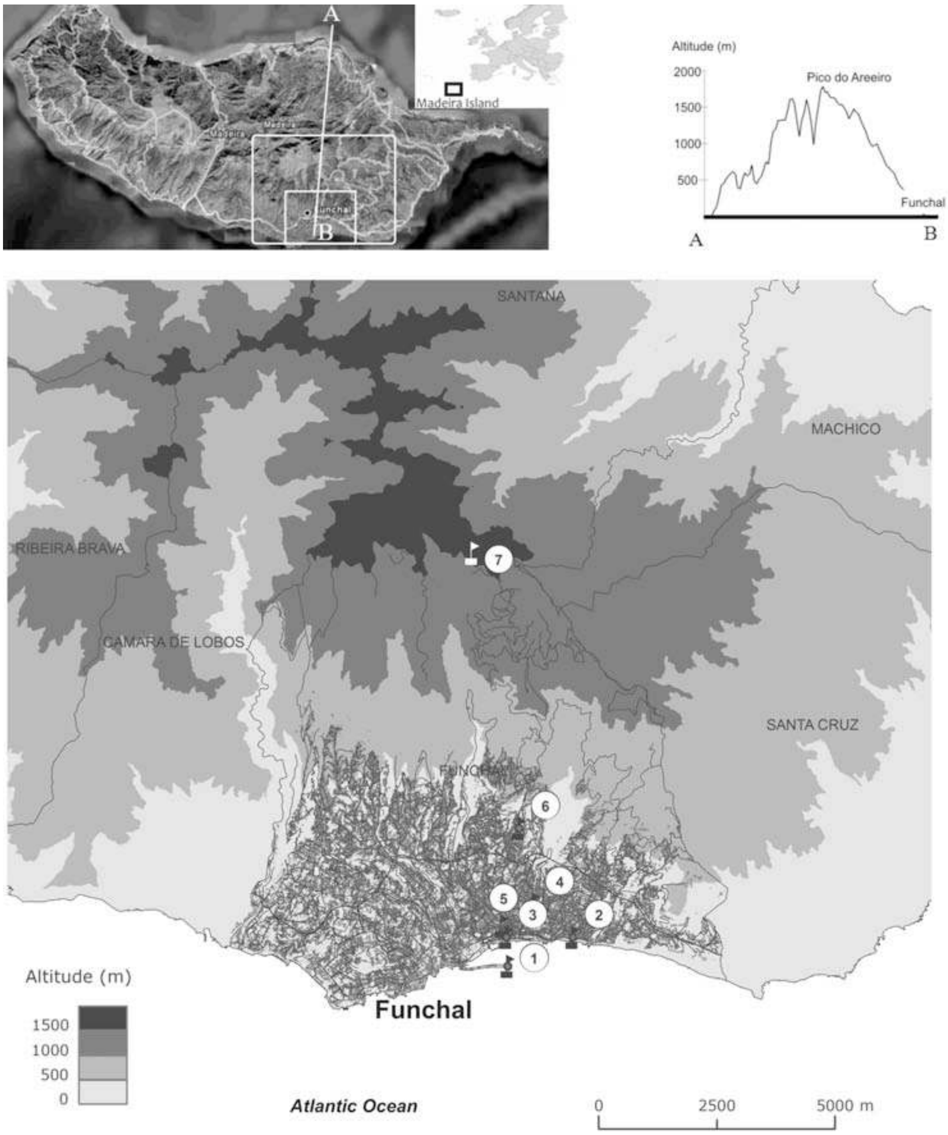

Figure 1: Madeira Island and Funchal region. Meteorological observation sites: 1 Pontinha; 2 Funchal/Obs.; 3 Police Station; 4 Firemen Station; 5 Museum; 6 Hospital; 7 Pico do Areeiro. Sources: Image ©2010 SRES DRIGOT; ©2010 Tele Atlas; Data SIO, NOAA, U.S. Navy NGA, GEBCO; ©2010Google; LOPES (2007).

2008a), but adverse and unexpected weather can limit outdoor activities. This issue is of great relevance and several studies show that agents in the tourism business (both stakeholders and consumers) are concerned with the consequences of climate change on the choice of their holiday destination (MACHETE et al., 2010a, b).

Climate information is required for tourism activity and simple meteorological or climatological parameters in the form of averages, extremes and frequencies may not be sufficient (MATZARAKIS, 2006 and 2007b), because individuals are sensitive to particular combinations of meteorological parameters, rather than to single ones (ANDRADE et al., 2007). The climate information that is usually given to tourists is fuzzy, incomplete or inaccurate, although climate is generally regarded as a decisive factor for the attraction as a tourist destination. The study area is not an exception; there are hardly any publications on climate and tourism in Madeira (ALCOFORADO et al., 1999; LOPES et al., 2010) and this is the first attempt to apply knowledge about sea breezes systems to urban planning and tourism activity. In addition, the incorporation of sea breeze characteristics within the modern thermal indices is firstly performed in the present study.

Funchal has been chosen due to the great number of visitors and tourists; furthermore, the steep slopes near the sea produce complex interactions between the sea and mountain breezes, the knowledge of which can prove useful in urban and tourism planning. Therefore, this research aims at investigating the interactions between sea breezes and regional winds in Funchal, an urban touristic area, and their influence on thermal com-

Table 1: Geographical characteristics of the observations sites (see locations in Fig. 1). Distances were measured horizontally to data points (Porto Santo, 1995).

Site	Nº in Fig. 1	Altitude (m)	Urban/topographic characteristics	Distance from the sea front (m)
Pontinha	1	5	Sea shore (Funchal Marina)	≈540 Offshore
Funchal/Obs.	2	58	Suburban medium density.	≈100
Police Station	3	10	Urban near the shore line	≈75
Firemen Station	4	50	Urban (valley bottom)	≈780
Museum	5	20	Urban (high density)	≈330
Hospital	6	380	High city; suburban surrounded by vegetation.	≈2370
Pico do Areeiro	7	1610	High mountain	≈10000

fort during hot periods. This study is also a contribution to tourism and urban planning and will be essential for a future research in which guidelines of good practices for both activities will be presented. A brief review of literature is presented in the next section. Section 3 deals with methodology and data used in this paper. The results are presented in section 4, followed by the discussion and the conclusion.

2 Literature review

Thermal comfort is the psychological state of mind that expresses people's satisfaction with the thermal surroundings and is usually referred to in terms of whether someone is feeling too hot or too cold (MAYER, 2008). It can be also defined as the environmental condition that is acceptable to 80 % or more of the occupants within a space (ASHRAE, 2004). Therefore, environmental conditions, metabolic processes and personal sensations create a complex balance with respect to human thermal comfort. Thermal discomfort can be more intense in urban areas, as temperature levels are higher in the centre of a city than in its suburbs causing an urban heat island effect, especially when the wind is week (bellow 5 m/s at 10 m high) (KOLOKOTRONI and GIRIDHARAN, 2008). This combination of high temperatures and poor ventilation reduces air quality and increases health risks affecting the quality of life in the cities. Especially during heat wave episodes, thermal stress can cause serious health problems and increase mortality and morbidity in humans (PAPANASTASIOU et al., 2010).

In a study about the impact and measures of adaptation to climate change in Madeira archipelago, the Physiologically Equivalent Temperatures (PET) was used to evaluate thermal comfort (CASIMIRO and LOURENÇO, 2006). The authors found that for the control period (1970–1999) high thermal stress occurred on 50 % of the summer days (from July to September). In the future, these hot periods may become more severe and the warm season may be longer.

Sea breezes are thermally driven wind systems that develop in coastal areas during days with strong atmospheric stability, clear skies and a significant temperature difference between the land and the sea. In mid-latitude and Mediterranean regions, sea breezes are more frequent and persistent in spring and summer, but they can also occur in other seasons in areas with a large number of sunny days and where the thermal gradient is sufficient to trigger the system (ALCOFORADO, 1987; AZORIN-MOLINA et al., 2009).

Sea breezes begin to blow generally two hours after sunrise with hourly intensities about 3 to 4m/s during the day (SIMPSON, 1994). In the Mediterranean coast of Alicante and on the island of Majorca in Spain (RAMIS et al., 1990; AZORIN-MOLINA et al., 2009), as well as in Funchal (LOPES, 2007; LOPES et al., 2010), an average permanence period of 4 to 5 hours after sunset was reported.

The intrusion of cool air associated with sea breeze circulation increases the relative humidity and inhibits air temperature rise, hence ameliorating urban coastal environment and improving thermal comfort conditions with consequent effects on human health and even on plant physiology (ZHU and ATKINSON, 2004; BONNARDOT et al., 2005; PAPANASTASIOU et al., 2010).

During summer heat waves in the Aegean coast of Greece (Volos area), PAPANASTASIOU et al. (2010) found a decrease in temperature up to 8.2 ºC when sea breezes occur near the shore line. Consequently, people living near the coast feel less uncomfortable during daytime.

In Lisbon it was found that even if the breezes do not travel very far inland, they play an important role in cooling the urban air near the river bank, where air temperature may be up to 6 ºC (or more during strong SW breeze) lower than in the city centre (Alcoforado, 1987; Alcoforado et al., 2009).

However, the influence of sea breezes within urban environments is not a completely advantageous factor because it can bring health problems related to the weak capacity of atmospheric pollutant dispersion under these conditions. Several studies point out an impoverishment of air quality and the increase of PM10 levels in the urban atmosphere, strongly enhancing the formation of secondary aerosols due to the character of the close circulation of this system (Colbeck et al., 2002; Rodríguez, et al., 2008).

Local economies can be favoured by this local climatic feature. In the above mentioned study about the characteristics of the sea breeze flow in the Bay of Alicante, south-eastern Spain, Azorin-Molina et al. (2009), stated that sea breezes are also an important climate resource to be considered because of their economic impacts on tourism activities, sports and services, which are the main economic sectors of many coastal regions.

In order to get an appropriate thorough assessment of thermal comfort in Funchal considering effects of air temperature, air humidity, wind speed and radiation fluxes during hot days, a methodology based on the estimation of PET (Physiologically Equivalent Temperature) was applied. PET is one of the most commonly used thermal comfort indices and it can be defined as the air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed (Mayer and Höppe, 1987; Höppe, 1999). Furthermore, PET is a standard that has been widely applied for the prediction of changes in the thermal component of urban and regional planning studies (VDI, 1998; Höppe, 1999; Matzarakis et al., 1999).

PET has been widely used not only in middle European regions and in cold climates (Endler and Matzarakis, 2011; Grigorieva and Matzarakis, 2010), but also in other sub-tropical, tropical and monsoon regions (Matzarakis, 2006, 2008; Matzarakis and Amelung, 2008; Lin and Matzarakis, 2008a, b; Lin and Matzarakis, 2011). In order to justify the use of PET in the studied area, it must be said that this thermal index has also been tested and applied in Lisbon, a Mediterranean climate with Atlantic influences (Alcoforado et al., 2004; Oliveira and Andrade, 2007; Andrade and Alcoforado, 2008) and in other Mediterranean areas (Matzarakis 2007a; Didaskalou et al., 2004; Morabito et al., 2004a, b; Grifoni et al., 2004).

The relevance of this index lies in the fact that in addition to being based on meteorological parameters, it reproduces the physiological human response to the environment, making it possible to assess the indoor and outdoor thermal conditions (Matzarakis and Mayer, 1996). PET is a real climatic index describing the thermal environment which enables a layperson to assess the thermal component of climate on the basis of personal experience (Höppe, 1999). One of the problems related to this methodology is the difficulty to get the complete input data to compute PET. In this research, Rayman software (Matzarakis et al., 2007) was used to estimate all the parameters that are not usually collected by meteorological stations, like the mean radiant temperature or water vapour pressure. The details about the estimation of PET are presented in the section 3.

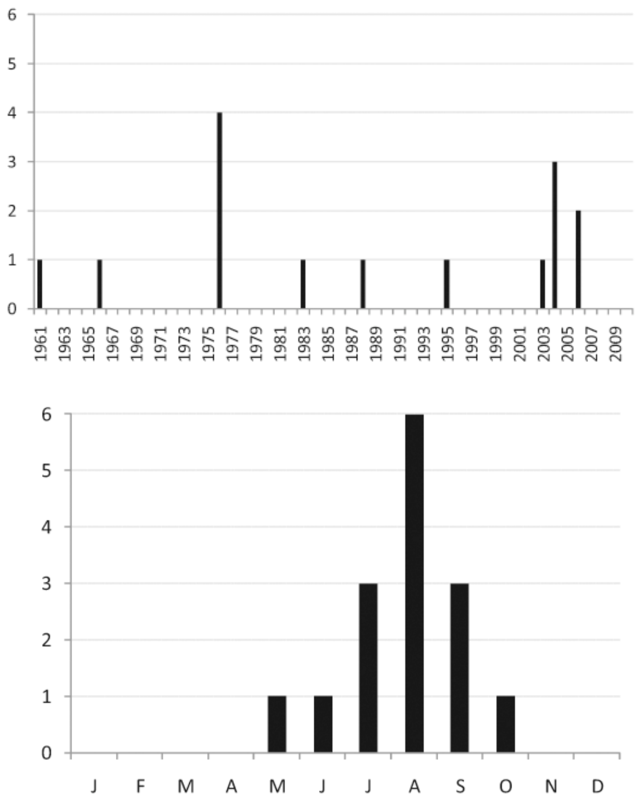

Figure 3: Hot periods identified by the yellow warning criteria of the Civil Protection in Madeira: top: number of hot days; bottom: period of occurrence.

3 Data and methods

Several micro meteorological stations (Fig. 1 and Table 1 – except 2 and 7 that belong to the Institute of Meteorology) measuring temperature, relative humidity, wind direction, and wind speed have been operated by the Regional Laboratory of Civil Engineering (LREC) in Funchal since January 2006.

Temperature, wind speed and direction, relative humidity and global radiation were measured at 12:00 h and 18:00 h, local time. Rayman software was used to calculate, among other parameters, the Physiologically Equivalent Temperature (PET) (Matzarakis et

Table 2: Maximum, minimum temperature and daily anomalies in Funchal/Observatory during the "hot days" period (3 to 6 of September 2006).

Date	Tmin (ºC)	Anomaly (ºC)	Tmax (ºC)	Anomaly (ºC)
03-09-2006	21.2	+1.7	32.8	+6.6
04-09-2006	24.7	+5.1	33.3	+7.0
05-09-2006	24.6	+4.9	34.3	+7.8
06-09-2006	22.6	+2.8	30.7	+4.0

al., 2007) and Mean Radiant Temperature (MRT), the uniform temperature of a black enclosure in which a subject would exchange the same heat flow by radiation as in the actual environment (LAGENNUSA et al., 2005).

The characteristics of sea breezes were identified using temperature and wind speed and direction from May to October 2006. Two criteria were used to consider the occurrence of sea breezes: i) the change in the wind direction (sea-land) after sunrise, necessarily opposite to the general wind on top of the mountain (Pico do Areeiro); ii) the identification of a thermal difference of 1ºC between Pontinha, in the Funchal Marina (1 in Fig.1 and Table 1) and the Museum, inside the city (5 in Fig. 1 and Table 1).

According to PETERSON et al. (2001), a heat wave occurs when there is a period of six consecutive days with temperatures 5ºC over the average value in the reference normal. However, this definition has been considered more suitable for climate variability studies than for the assessment of human health and thermal comfort. Considering this definition, no such events were found in the last 50 years at the meteorological station of Funchal/Observatory.

In the present research, the methodology applied in the assessment of the "Natural and Anthropogenic Hazards in Funchal" (CMF, 2011) was used (see section 1.2). This methodology considers a "high temperature day" when the maximum temperature is $\geq$ 32ºC and the minimum temperature is $\geq$ 24ºC). The total number of hot days between 1961 and 2009 is presented in Fig. 3.

Within this data set, two groups of days from May to October 2006 were selected to study the influence of sea breeze on the thermal comfort at several places in Funchal: i) The first group correspond to "average days" with sea breeze (total of 10 days from June to August). Within this group, the average of maximum and minimum anomalies did not exceed 1.5ºC. ii) In the second group (3 to 6 September – Table 2), the temperature was much higher than the average values for the period. However, although the negative effects were initially reported in the local media on the 3^{rd} of September, only the 4^{th} and the 5^{th} meet the above referred thermal criteria. Therefore, the study period was extended from the 3rd to the 6th of September.

The temperature anomalies were +3.6 ºC for minimum and +6.4ºC for maximum temperatures. Except in Pontinha (near the shore) and at the Hospital (in a higher altitude), all the observation sites registered temperatures around 29/30ºC and PET above 38ºC at 12:00 h (Table 3). Therefore, these days were classified as "hot days".

4 Results

4.1 Sea breezes in Funchal

In summer, the eastern flank of the Azores anticyclone controls this part of the Atlantic and the northeast wind prevails on Madeira Island. However, in the Funchal region the dominant flux is replaced by a persistent south and southwest breeze during the day, while during the night there is usually a north mountain breeze (Fig. 4).

On the top of the mountain (Pico do Areeiro) the wind blows prevailingly from the NE with a mean speed of about 7 m/s, while the sea breeze blows in Funchal and up the mountain as a valley breeze. The central mountain of Madeira acts as a barrier to the synoptic wind and on the southern slope the wind is highly modified by the relief and influenced by thermal differences between the sea and the land.

In Funchal several types of sea breezes, defined by their characteristics (predominant wind direction and speed, duration, existing of veering dynamics or intermittence – see criteria in section 3) were identified by LOPES (2007). During the period studied (May to October 2006), sea breezes occurred on 84 % of the days, showing the persistence of this local wind system in the southern part of Madeira. Table 4 shows the principal characteristics of the breezes.

Sea breezes usually start in the morning (after 9:30h) and end at night (usually after 22:00 h, but can occasionally persist until 23:00 h), with an average total duration of about 12:50 hours and a mean velocity of 2.9 m/s. These patterns are very similar to those reported in other places (AZORIN-MOLINA et al., 2009), especially the average duration and the times of occurrence. However, due to the mountains north of Funchal, the extent and influence of sea breezes is limited in space, generally to 400 m of altitude (3 to 4 km inland), although the progression is estimated to occur only on the bottom of the valleys that are free of constructions. However, studies about ventilation paths should be performed to confirm this, using the methodology successfully applied in Lisbon (ALCOFORADO et al., 2009).

Due to its persistence, sea breeze is an important factor to improve thermal comfort in Funchal and to be taken into account in urban planning. The final goal of this analysis is to evaluate the influence of sea breeze on average days and on hot days and to assess the urban areas that are more positively affected by this wind system.

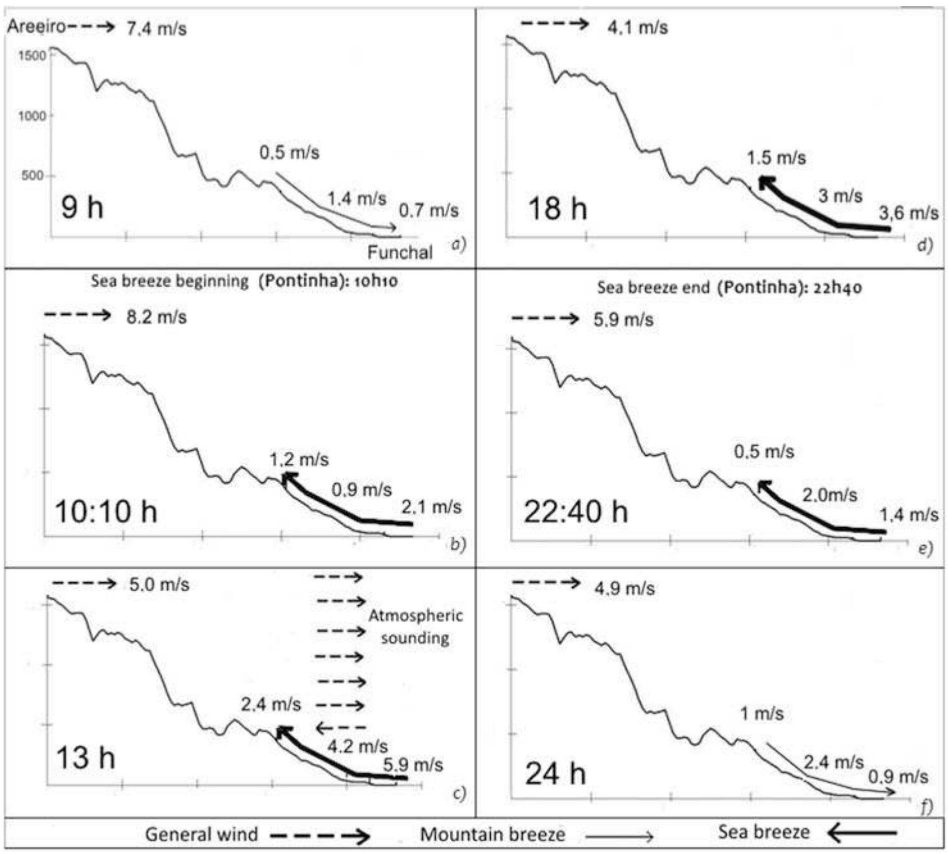

Figure 4: Typical sea and mountain breezes during a summer day (27$^{\text{th}}$ August 2006).

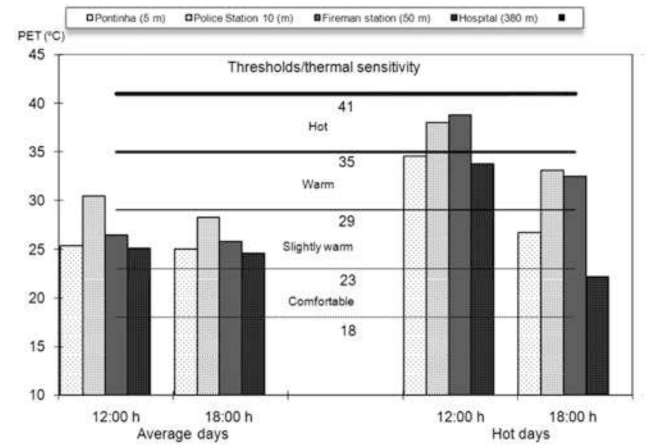

Figure 5: Estimated PET for the two groups of days. Thermal sensitivity "Slightly warm" class corresponds to a grade of physiological stress of "Slight heat stress"; "Warm" to "Moderate heat stress"; and "Hot" to "Strong heat stress" (according to MATZARAKIS and MAYER, 1996).

4.2 Thermal comfort during "average days" and "hot days"

On average summer days the thermal sensitivity at 12:00 h is slightly warm at all measured locations (air temperature = 23.4°C; MRT = 48.7°C and PET = 27.8°C – Table 5), denoting the slight heat stress character inside the city of Funchal (Fig. 5). A small improvement in thermal comfort is observed in the afternoon (18:00 h), although the thermal sensitivity continues to be the same (PET = 27°C).

During a period of hot days, the eastern flux from North Africa (Fig. 6) was regular and the wind blew with an average speed of 1.8 m/s in Funchal. This wind was replaced at the end of the afternoon by a land breeze, maintaining high air temperatures during the night in Funchal (mean temperatures around 27.7°C at 18:00 h). Relative humidity was very high, with values of 90 % near the shore (Table 3) and above 50 % at the other observation points inside the city.

Hot days are clearly more uncomfortable, especially at 12:00 h inside the city of Funchal (air temperature = 27.5°C; MRT = 55.7°C and PET = 36.8°C – Table 5), when thermal sensitivity is "hot" and "strong heat stress can occur" (Fig. 5). The best location is near the shore line (Pontinha, 1 in Fig. 1) where the wind speed is higher (2.5 to 3 m/s) than in the inner city (1.3 to 1.7 m/s). Generally, a wind speed reduction of about 30–40 % is typical present in urban areas where the aerodynamic roughness length increases up to 1 m (LOPES et al., 2011).

According to HÖPPE (1999), air temperature is more important than the MRT on days with strong winds,

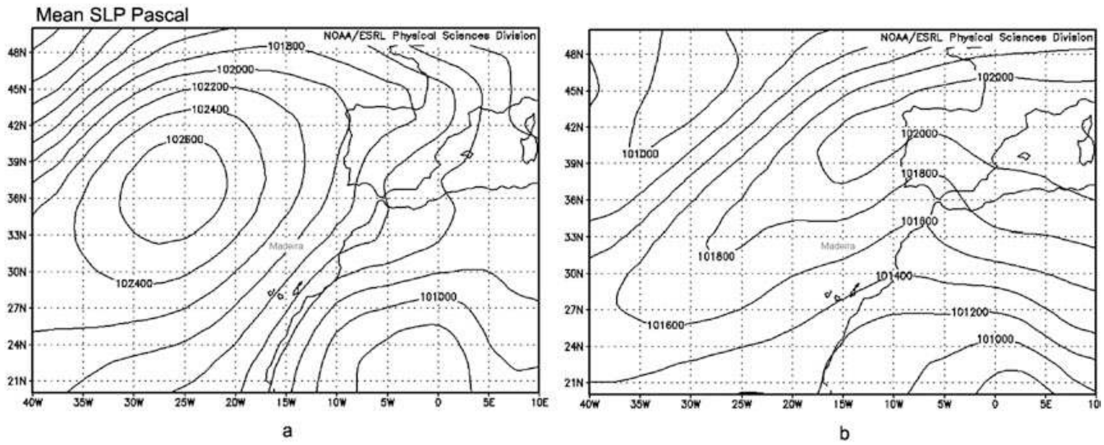

Figure 6: NCEP/NCAR reanalysis (KALNAY et al., 1996) of the 1st of August (a), representing breeze days and 3rd of September 2006 (b), showing the "African" eastern flux.

Table 3: Meteorological parameters measured in the LREC network (RH – relative humidity, Temp – air temperature and U – wind speed) and estimated by Rayman software (MRT – mean radiative temperature and PET – physiologically equivalent temperature), during "average days" and "hot days".

Average days										
	12:00h					18:00h				
Location	RH (%)	Temp. (°C)	U (m/s)	MRT (°C)	PET (°C)	RH (%)	Temp. (°C)	U (m/s)	MRT (°C)	PET (°C)
Pontinha	82.5	22.5	2.7	44.6	25.3	81.2	22.9	3.5	38.0	25.0
Police Station	62.2	25.0	2.4	50.1	30.4	61.6	25.5	3.0	40.0	28.2
Firemen Station	68.7	22.9	2.6	48.7	26.4	70.0	23.4	2.7	38.3	25.8
Hospital	76.2	21.3	2.2	47.3	25.1	76.0	21.6	1.9	36.8	24.6
Hot days										
	12:00h					18:00h				
Location	RH (%)	Temp. (°C)	U (m/s)	MRT (°C)	PET (°C)	RH (%)	Temp. (°C)	U (m/s)	MRT (°C)	PET (°C)
Pontinha	94.7	25.3	2.5	56.1	34.5	86.0	27.0	3.0	33.9	26.7
Police Station	63.3	28.7	2.3	58.1	**38.0**	47.3	30.8	1.8	40.1	**33.1**
Firemen Station	50.1	29.2	1.3	54.8	**38.8**	47.4	30.0	1.6	39.6	**32.4**
Hospital	82.3	23.9	1.7	55.8	33.7	87.0	22.3	1.3	30.0	22.2

because air temperature dominates the convective heat exchange. Conversely, under light wind conditions (like the present situation) the MRT has roughly the same importance for the heat balance of the human body as the air temperature. During hot days, a reduction of the uncomfortable situations in the afternoon (from hot to warm) can be explained by the decrease of global radiation (870 W/m^2 at noon to 240 W/m^2 at 18:00 h) and a consequent decrease of 17°C of MRT.

In both cases (average and hot days), locations near the shore line (Pontinha) are always much more comfortable than other places. Especially during hot days, better levels of thermal comfort can be found in the suburban elevated sites of Funchal surrounded by green spaces (such as near the Hospital, located at 380 m). The places inside the city (even near the ocean) surrounded by dense construction (like near the Police station), may be slightly warmer (moderate heat stress) even during average days (Fig. 5). People would feel strong heat stress inside the city at noon (with PET values above 38°C in the Police and Fireman sites – Table 3) during hot days (Fig. 5).

To understand the importance of sea breezes during hot periods a more detailed analysis of PET, wind speed and air temperatures was made for the sample of hot days (Fig. 7). The investigation revealed the role of the urban structure in the impoverishment of human comfort conditions and the importance of sea breeze for the amelioration near the coast. This can be verified by the differences between the Firemen and Police Station observation sites and Pontinha (the last being 4 to 5°C cooler in average) with a maximum difference of 16 to 19°C during the day.

Table 4: Characteristics of the sea breeze in Funchal (Pontinha), from May to September 2006. Source: LOPES, 2007.

Type	Dominant direction	Beginning (median)	End (median)	Duration in hours (avg.)	Mean wind speed (m/s)
Regular	SW	9:30	23:10	13:40	4.0
	S and SE	10:00	21:40	11:40	1.9
Irregular	Other with veering	9:30	22:20	12:50	3.0
General Characteristics	SW to SE	≈9:40	≈22:30	≈12:50	2.9

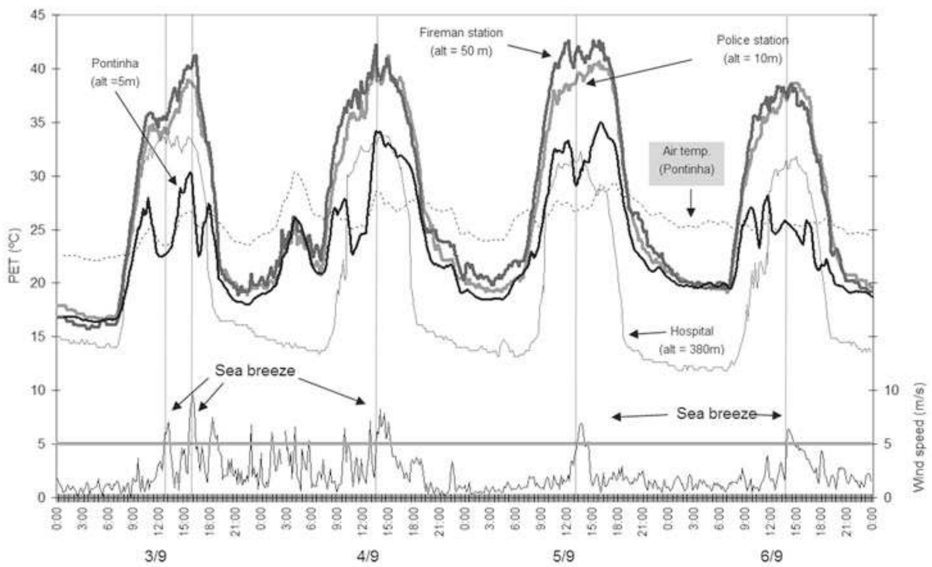

Figure 7: PET during hot days (from 3 to 6 September 2006). The wind data was collected in Pontinha (Funchal Marina).

As mentioned above, the coastal areas are pleasant locations during hot periods due to the proximity of the ocean, especially when more intense sea breezes reach inland. This can be seen immediately after 12:00 h on September 3rd, when the wind speed exceeded 5 m/s and the PET suddenly decreased about 8°C near Pontinha (Fig.7). The breeze did not immediately affect the air temperature inside the urban dense areas, where a maximum PET value was registered. About 4 to 5 m/s wind speed seemed to be the trigger to alleviate thermal stress, although the average air temperature stayed relatively high (above 25°C). During night-time temperatures tended to be stable near the shore and inside the urban structure. The best comfort conditions can be found in the highest places in the Funchal suburban green areas (near the Hospital observation site) where PET values are on average 7°C lower than inside the urban compact structure (Firemen and Police Station) during day time.

5 Discussion and conclusions

Most of the tourists that choose Madeira as a travel destination are aged between 40 and 70, come from northern European countries (71 %), are not used to hot environments and are vulnerable to thermal stress.

However, despite its established importance, little attention is given to Madeira's climate as a factor of attraction. For example, the most important climate information on the official site of Madeira Tourism (www.madeiraislands.travel, last visited in May 2011) is seasonal air and sea temperatures and only a "climate chart" is provided (with monthly average temperatures, total sunshine hours and precipitation). Although climate is seen by travel operators as an attraction factor for tourism, the climate information that is generally given to the tourists is clearly insufficient because current market rules impose accurate reporting to the consumers (COUTO and LOPES, 2010).

Furthermore, simple meteorological or climatological parameters in the form of means, extremes and frequencies may not be useful (MATZARAKIS, 2006 and 2007b), because individuals are sensitive to particular combinations of meteorological parameters, rather than to single ones (ANDRADE et al., 2007). Data dissemination should be reformulated and the use of different but effective methodologies has been proposed by the author's research groups. ALCOFORADO et al. (1999) ap-

Table 5: Average meteorological conditions during average days and hot days in the studied period (summer 2006).

	12:00h					18:00h				
	RH (%)	Temp. (ºC)	U (m/s)	MRT (ºC)	PET (ºC)	RH (%)	Temp. (ºC)	U (m/s)	MRT (ºC)	PET (ºC)
Average days	70.6	23.4	2.4	48.7	27.8	71.8	23.5	2.5	40.9	27.0
Hot days	67.0	27.5	1.8	55.7	36.8	64.3	27.7	1.8	36.4	29.1

plied a methodology based on the frequency of weather types per decades to present the climate of Funchal for tourism purposes. ANDRADE et al. (2007), based on the same methodology of weather types but including PET instead of air temperature, assessed the conditions for seaside recreation activities in Praia Grande, Sintra (Portugal); the innovation of this research consisted of combining bioclimatic indices and indirect surveys about the perception of atmospheric conditions felt by people on the beach. MATZARAKIS (2007a) suggested a Climate-Tourism-Information-Scheme (CTIS), which is meant to be a "clear and user friendly visualization for information transfer (...) to be based on scientific knowledge". This scheme is based on bioclimatic (PET), tourism climatic factors (temperature, wind speed, precipitation, and vapour pressure) and aesthetic components (cloudiness and fog) in the form of frequencies and probabilities of occurrence. The information produced is a classification of positive or negative ranked factors and is presented in a simple way (MATZARAKIS et al., 2010).

Based on the findings of this research and supported by some of the methodologies mentioned above, a framework that will combine climate information of effective use to tourism and urban planning guidelines will be established.

This research leads to the following conclusions:

a) On an average summer day the climate of Funchal is generally comfortable (thermal sensitivity is "slightly warm") at all measuring sites, even inside the urban fabric, although close to the threshold between "slightly warm" and "warm" conditions.

b) During "hot days" no absolute comfort situation was observed especially at noon inside the city of Funchal. People staying in the more densely built part of Funchal may then experience strong heat stress. However, near the shore line the sea breeze is effective in reducing heat stress. The highest locations are also recommended places to stay due to the altitudinal effect and to the presence of forests.

c) By the end of the day the levels of stress become acceptable near the shoreline and at the highest sites even during hot days, where the atmospheric environment may be "slightly warm" or even "comfortable". However, the inner city remains "hot" probably because the ventilation is hampered by the buildings and the heat island may be intensified.

d) Sea breezes are important to mitigate heat stress and urban planners should take advantage of them and avoid promoting dense construction near the shoreline that would act as a barrier to air renewal inside the city. Therefore, ventilation paths perpendicular to the coastline and directed to the city-centre are of utmost importance to prevent thermal stress.

The current work is a first step to help solving possible conflicts between a built environment and tourism activities in coastal areas and to create future climatic guidelines for planning in Funchal in order to contribute to the sustainability of the urban environment. Some guidelines can already be proposed:

i) Tourism planners and local authorities should provide solutions to mitigate the negative effects on thermal comfort during hot periods, including a system to provide information and advice to the more vulnerable individuals. Concerning tourism, the information should be primarily directed to hotels, but can also be supplied to other activities/institutions (nurseries and nursing homes). If this plan is conveniently divulged in combination with other components (climate, beauty of the island, gastronomy, cultural values, etc.) by tourism agencies, it can attract elderly visitors by making them "feel" more secure and safe.

ii) In the sequence of the above guideline, local authorities can advise more vulnerable people to remain near the shore line during the hottest time of day. Other ways to avoid the negative consequences to health during hot periods may be the implementation of alternative activities, such as boat trips, short trips to places located at altitudes above 400 m (outside the city of Funchal) or in controlled environments (visits to gardens and museums) during these periods.

iii) Ventilation paths should be left unobstructed in new development areas in order to ameliorate the urban environment. As was shown, sea breezes are a functional effective way of cooling outdoor spaces, improving the urban environment and saving energy by reducing climatization costs.

In future studies, other components like atmospheric pollutants, bioaerosols (especially pollens), and its dispersion conditions must be studied in order to assess the quality of the air in the Funchal urban area. Models based in CFD can be used to determine the dispersion conditions using the findings and results obtained with the present research as inputs. This knowledge will benefit those engaged in planning healthier cities and those who will continue to prefer nice weather, security and high-quality urban environment.

Acknowledgments

We would like to thank the anonymous reviewers for their very constructive and detailed comments. The research leading to these results has received funding from the European Community's Seventh Framework Program FP7/2007-2013 under grant agreement n° 244251 (http://www.projectsecoa.eu/; Solutions for Environmental Contrasts in Coastal Areas).

References

ALCOFORADO, M.J., 1987: Brisas estivais do Tejo e do Oceano na região de Lisboa. – Finisterra – Revista Portuguesa de Geografia XXII (43), 71–112.

ALCOFORADO, M.J., A. DIAS, V. GOMES, 1999: Bioclimatologia e turismo, exemplo de aplicação ao Funchal. – Islenha **25**, 29-37.

ALCOFORADO, M. J., H. ANDRADE, M.J. VIEIRA PAULO, 2004: Weather and recreation at the Atlantic shore near Lisbon, Portugal: a study on applied local climatology. – In: MATZARAKIS, A., C. R. DE FREITAS, D. SCOTT (Eds): Advances in Tourism. – Climatology. Ber. Meteor. Inst. Univ. Freiburg Nr. **12**, 38–48.

ALCOFORADO, M.J., H. ANDRADE, A. LOPES, J. VASCONCELOS, 2009: Application of climatic guidelines to urban planning. The example of Lisbon (Portugal). – Landscape and Urban Planning **90**, 56–65.

ANDRADE, H., M. J. ALCOFORADO, 2008: Microclimatic variation of thermal comfort in a district of Lisbon (Telheiras) at night. – Theo. Appl. Climatol. **92**, 225–237.

ANDRADE, H., M.J. ALCOFORADO, S. OLIVEIRA, 2007: Methodologies to assess the effects of climate on tourism: weather type and individual perception. – In A. MATZARAKIS, C. R. DE FREITAS, D. SCOTT (Eds): Developments in tourism climatology, Commission on Climate and Recreation, 74–79.

ASHRAE, 2004: Thermal environmental conditions for human occupancy – Standard 55. – American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta.

AYRES, J., B. FORSBERG, I. ANNESI-MAESANO, R. DEY, K. EBI, P. HELMS, M. MEDINA-RAMÓN, M. WINDT, F. FORASTIERE, 2009: Climate change and respiratory disease: European Respiratory Society Position Statement t. – European Respiratory Journal **34**, 295–302.

AZORIN-MOLINA, C., D. CHEN, S. TIJM, M. BALDI, 2009: A multi-year study of sea breezes in a Mediterranean coastal site: Alicante (Spain). – Int. J. Climatol. **31**, 468–486.

BONNARDOT, V., O. PLANCHON, S. CAUTENET, 2005: Sea breeze development under an offshore synoptic wind in the South-Western Cape and implications for the Stellenbosch wine-producing area. – Theor. Appl. Climatol. **81**, 203–218.

CASIMIRO, E., T. LOURENÇO, 2006: Turismo. – In SANTOS, F.D., R. AGUIAR (Eds): Impactos e medidas de adaptação às alterações climáticas no arquipélago da Madeira. – Projecto CLIMAAT II, DRAM, Funchal.

CMF, 2011: Emergency Plan of the Municipality of Funchal, Municipia, Lisboa. – (restricted document).

COLBECK, I., C. MENG-CHEN, K. ELEFTHERIADIS, 2002: Formation and transport of atmospheric aerosol over Athens, Greece. – Water Air Soil Pollut. Focus **2**, 223–235.

COUTO, J., A. LOPES, 2010: A informação climática disponibilizada pelas agências e operadores turísticos. – II Workshop Internacional sobre Clima e Recursos Naturais nos Países de Língua Portuguesa, IPB, Bragança.

DE FREITAS, C.R., 2003: Tourism climatology: evaluating environmental information for decision making and business planning in the recreation and tourism sector. – Int. J. Biometeor. **48**, 45–54.

DIDASKALOU, E.A., P.TH. NASTOS, A. MATZARAKIS, 2004: The development prospects for Greek health tourism and the role of the bioclimate regime in Greece. – In: MATZARAKIS, A., C.R. DE FREITAS, D. SCOTT (Eds): Advances in Tourism Climatology. – Ber. Meteor. Inst. Univ. Freiburg Nr. **12**, 149–157.

ENDLER, C., A. MATZARAKIS, 2011: Climatic and tourism related changes in the Black Forest: Winter season. – Int. J. Biometeor. **55**, 339–351.

GRIFONI, D., G. MESSERI, M. PASQUI, A. CRISCI, M. MORABITO, B. GOZZINI, C. TEI, G. CAR-RERAS, M. ROSSI, F. PASI, G. ZIPOLI, 2004: A developing operational system to support tourism activities in Tuscany Region. – In: MATZARAKIS, A., C. R. DE FREITAS, D. SCOTT (Eds): Advances in Tourism Climatology. – Ber. Meteor. Inst. Univ. Freiburg Nr. **12**, 180-188.

GRIGORIEVA, E.A., A. MATZARAKIS, 2010: Physiologically equivalent temperature in extreme climate regions in the Russian Far East. – In: MATZARAKIS, A., H. MAYER, F.-M. CHMIELEWSKI (Eds): Proceedings of the 7th Conference on Biometeorology. – Ber. Meteorol. Inst. Univ. Freiburg No. **20**, 386–391.

HÖPPE, P., 1999: The physiological equivalent temperature. A universal index for the biometeorological assessment of the thermal environment. – Int. J. Biometeor. **43**, 71–75.

KALNAY et al., 1996: The NCEP/NCAR 40 year reanalysis project. – Bull. Amer. Meteor. Soc. **77**, 437–470.

KOLOKOTRONI, M., R. GIRIDHARAN, 2008. Urban heat island intensity in London: an investigation of the impact of physical characteristics on changes in outdoor air temperature during summer. – Solar Energy **82**, 986–998.

LAGENNUSA, M, A. NUCARA, G. RIZZO, G. SCACCIANOCE, 2005: The calculation of the mean radiant temperature of a subject exposed to the solar radiation – a generalised algorithm. – Build. Environ. **40**, 367–375.

LIN, T.-P., A. MATZARAKIS, 2008a: Climate-tourism analysis and application of tourists flow forecast in Taiwan. – Proceedings 18th International Congress on Biometeorology, 1–4.

—, —, 2008b: Tourism climate and thermal comfort in Sun Moon Lake, Taiwan. – Int. J. Biometeor. **52**, 281–290.

—, —, 2011: Tourism-climate information based on human thermal perception in Eastern China and Taiwan. – Tourism Management **32**, 492–500.

LOPES, S., 2007: Summer wind regimes in Funchal related with thermal patterns, Master Thesis in Geography, Climate and Society. – University of Lisbon, (in Portuguese with an extended abstract in English).

LOPES, A., S. LOPES, A. MATZARAKIS, M.J. ALCOFORADO, 2010: Summer sea breeze influence on human comfort in Funchal (Madeira Island). Application to urban climate and tourism planning. – In: MATZARAKIS, A., H. MAYER, F.-M. CHMIELEWSKI (Eds): Proceedings of the 7th Conference on Biometeorology. – Ber. Meteorol. Inst. Univ. Freiburg **20**, 352–357.

LOPES, A., J. SARAIVA, M.J. ALCOFORADO, 2011: Urban boundary layer wind speed reduction in summer due to urban growth and environmental consequences in Lisbon. – Environ. Model & Soft. **26**, 241–243.

MACHETE, R., A. LOPES, J.C. COUTO, 2010a: Perception of tourists about the consequences of predicted climate change in Lisbon. – International Congress on Tourism, CIT 2010 Heritage and Innovation, Porto.

MACHETE, R., C. FERREIRA, E. BRITO-HENRIQUES, H. ANDRADE, J.C. COUTO, 2010b: Anticipating the impacts of climate change on tourism in Lisbon Metropolitan Area – Assessing tourist perceptions. – In: MATZARAKIS, A., H. MAYER, F.-M. CHMIELEWSKI (Eds): Ber. Meteorol. Inst. Univ. Freiburg **20**, 346–351.

MAOTDR, 2007: Programa Nacional da Política de Ordenamento do Território, Lisboa. – www.territorioportugal.pt/pnpot/Storage/pdfs/PNPOT_RELATORIO.pdf [last consulted in May 2011].

MATZARAKIS, A., 2006: Weather and climate related information for tourism. – Tourism and Hospitality Planning & Development **3**, 99–115.

—, 2007a: Assessment method for climate and tourism based on daily data. – In: MATZARAKIS, A., C.R. DE FREITAS, D. SCOTT (Eds): Developments in Tourism Climatology 52–58.

—, 2007b: Climate, human comfort and tourism. - In: AMELUNG, B., K. BLAZEJCZYK, A. MATZARAKIS, A., (Eds): Climate change and tourism: assessment and coping strategies, 139–154.

—, 2007c: Climate and bioclimate information for tourism – the example of Evros prefecture. – In: MATZARAKIS, A., C. R. DE FREITAS, D. SCOTT (Eds): Developments in Tourism Climatology, 12–17.

—, 2008: Relevance of thermal bioclimate for tourism in Japan. – Global Environ. Res. **12**, 129–136.

MATZARAKIS, A., B. AMELUNG, 2008: Physiologically Equivalent Temperature as indicator for impacts of climate change on thermal comfort of humans. – In:. THOMSON, M. et al. (Eds): Seasonal Forecasts, Climatic Change and Human Health. – Advances in Global Change Research **30**, 161–172.

MATZARAKIS, A., H. MAYER, 1996: Another kind of environmental stress: thermal stress. – NEWSLETTERS No. 18, WHO Collaborating Centre for Air Quality Management and Air Pollution Control 7–10.

MATZARAKIS, A., H. MAYER, M. IZIOMON, 1999: Applications of a universal thermal index: physiological equivalent temperature. – Int. J. Biometeor. **43**, 76–84.

MATZARAKIS, A., F. RUTZ, H. MAYER, 2007: Modelling radiation fluxes in simple and complex environments – application of the RayMan model. – Int. J. Biometeor. **51**, 323–334.

MATZARAKIS, A., T. SCHNEEVOIGT, O. MATUSCHEK, C. ENDLER, 2010: Transfer of climate information for tourism and recreation – the CTIS software. – In: MATZARAKIS, A., H. MAYER, F.-M. CHMIELEWSKI (Eds): Proceedings of the 7th Conference on Biometeorology. – Ber. Meteorol. Inst. Univ. Freiburg **20**, 392–397.

MAYER, H., 2008: KLIMES – a joint research project on human thermal comfort in cities. – Berichte des Meteorologischen Instituts der Albert-Ludwigs Universität Freiburg Vol. **17**, 101–117.

MAYER, H., P. HÖPPE, 1987: Thermal comfort of man in different urban environments. – Theor. Appl. Climatol. **38**, 43–49.

MENESES, C.A., F.A. DA SILVA, 1946: Elucidário Madeirense Vol. 1. Funchal: DRAC (facsimile ed.). – www.bprmadeira.org/index_digital.php?IdSeccao=228 [last consulted in May 2011].

MORABITO, M., A. CRISCI, G. BARCAIOLI, G. MARACCHI, 2004a: Climate change: the impact on tourism comfort at three Italian tourist sites. – In: MATZARAKIS, A., C. R. DE FREITAS, D. SCOTT (Eds): Advances in Tourism Climatology. – Ber. Meteor. Inst. Univ. Freiburg Nr. **12**. 56–65.

MORABITO, M., L. CECCHI, P. A. MODESTI, A. CRISCI, S. ORLANDINI, G. MARACCHI, G. F GENSINI, 2004b: The impact of hot weather conditions on tourism in Florence, Italy: the summers 2002–2003 experience. – In: MATZARAKIS, A., C. R. DE FREITAS, D. SCOTT (Eds): Advances in Tourism Climatology. – Ber. Meteor. Inst. Univ. Freiburg Nr. **12**, 158–165.

OLIVEIRA, S., H. ANDRADE, 2007: An initial assessment of the climatic comfort in an outdoor public space of Lisbon. – Int. J. Biometeor. **52**, 69–84.

PAPANASTASIOU, D. MELAS, T. BARTZANAS, C. KITTAS, 2010: Temperature, comfort and pollution levels during heat waves and the role of sea breeze. – Int. J. Biometeor. **54**, 307–317.

PETERSON, T., C. FOLLAND, G. GRUZA, W. HOGG, A. MOKSSIT, N. PLUMMER, 2001: Report on the activities of the working group on climate change detection and related rapporteurs, 1998–2011. – World Climate Research Programme, WMO-TD No. 1071, IC-PO Publication Series **48**.

RAMIS, C., A. JANSÀ, S. ALONSO, 1990: Sea breeze in Mallorca. A numerical study. – Meteor. Atmos. Phys. **42**, 249–258.

RODRÍGUEZ, S., E. CUEVAS, Y. GONZÁLEZ, R. RAMOS, P. ROMERO, N. PÉREZ, X. QUEROL, A. ALASTUEY, 2008: Influence of sea breeze circulation and road traffic emissions on the relationship between particle number, black carbon, PM1, PM2.5 and PM2.5-10 concentrations in a coastal city. – Atmos. Environ. **42**, 6523–6534.

SANTOS F.D., R. AGUIAR (Ed.), 2006: Impactos e Medidas de Adaptação às Alterações Climáticas no Arquipélago da Madeira. – DRAM, Funchal, www.sra.pt/files/PDF/Destaques/Brochura%20CLIMAAT_II_MadeiraFINAL.pdf [last consulted in May 2011].

SIMPSON, J., 1994: Sea breeze and local winds. – Cambridge University Press, Cambridge.

VDI, 1998: Methods for the human-biometerological assessment of climate and air hygiene for urban and regional planning. Part I: Climate. – VDI guideline 3787. Part 2. Beuth, Berlin.

ZHU, M., B.W. ATKINSON, 2004: Observed and modelled climatology of the land-sea breeze circulation over the Persian Gulf. – Int. J. Climatol. **24**, 883–905.