International Journal of Biometeorology
https://doi.org/10.1007/s00484-018-01660-3

ORIGINAL PAPER

Evaluation of microclimates and assessment of thermal comfort of *Panthera leo* in the Masai Mara National Reserve, Kenya

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Received: 8 July 2018 / Revised: 19 November 2018 / Accepted: 4 December 2018

Abstract
Quantifying comfort levels of lions within the Masai Mara National Reserve in Kenya is the main focus of this study. Its discourse delineates step by step the process of quantifying comfort levels of lions within the Mara. Resource-efficient measures for humans in the built environment have long been developed through the creation of passive zones and modulated ventilation. In an analogous manner, new procedures are being adapted for creating optimized microclimates in natural game reserves. This involves CFD (computational fluid dynamics)-inspired landscaping. It is seen that the predicted mean vote (PMV) values—measures of thermal comfort—exceed the expected comfortable ranges suitable for normal functioning of lions in the reserve. This calls for a detailed exploration on sustainable development of this sanctuary. The paper illustrates how modern tools in computational fluid dynamics can be used along with standard ecological models to ascertain the optimal extent of airflow, levels of hydration, and land use pattern changes affecting the prevailing microclimate.

Keywords Game reserve resource efficiency · Airflow · Thermal comfort · Habitat preference · Microclimate

Introduction

The East African country of Kenya is home to the Masai Mara National Reserve, famous for its pristine wildlife and primeval habitats. The land supports animals in profusion—prides of lions (*Panthera leo*), crashes of rhinoceroses (*Diceros bicornis*, *Ceratotherium simum*), journeys of giraffes (*Giraffa camelopardalis tippelskirchi*, *Giraffa camelopardalis reticulate*, *Giraffa camelopardalis rothschildi*), and herds of elephants (*Loxodonta africana*) share a common habitat. Likewise, clans of hyena (*Crocuta crocuta*), drifts of warthogs (*Phacochoerus africanus*), dazzles of zebra (*Equus quagga*), troops of baboons (*Papio anubis*, *Papio cynocephalus*), rafts of hippopotamuses (*Hippopotamus amphibious*), and leaps of leopards (*Panthera pardus pardus*) along with herds of buffaloes (*Syncerus caffer*) throng the many hectares of open forests interspersed with the lakes and rivers within the Mara. The Masai Mara National Reserve (1.4900° S, 35.1439° E) is drained by the River Mara and its open vistas provide a unique microclimate to its occupants. However, with increasing urbanization, it is important to ascertain whether the reserve can sustain optimal levels of wind flow, moisture (relative humidity), and variations in temperature for the animals to be comfortable. The ASHRAE (American Society for Heating Refrigeration and Air conditioning) has prescribed a 7-point scale for optimal human comfort in occupied spaces. In this scale, the 0 point is most comfortable; + 3 is un-comfortably hot, while − 3 refers to frigid conditions. In this paper, we have attempted to explore whether the ASHRAE-recommended predicted mean vote values (PMV) are also obtained within the Mara. This involved the use of a suite of models—first, a Weather Research and Forecasting Model (WRF) sourced from NOAA (National Oceanic and Atmospheric Administration), USA, was used to decipher the soil category and the Leaf Area Index and the main atmospheric variables including temperature, relative humidity, and 3D wind velocity vectors. This was followed by using other downscaled CFD codes to obtain the airflow rates and humidity levels to be used in PMV estimates fashioned after Fanger's classic

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Published online: 24 January 2019

1972 paper. The projected comfort levels for a mammal with a four-chambered heart based on received levels of solar insolation, temperature, humidity, and wind speed variations vis-à-vis skin clothing (or fur in the case of animals) and metabolic activities could then be obtained.

Although visitors to this reserve marvel at its expansive wilderness, changing land use patterns and the growth of ranches and roads have led to habitat desiccation resulting in increased conflict of predators with Masai cattle (Kaufmann 1976). The changes in land cover and ungulate populations are corroborated by mechanized methods adopted by private landowners for the monopolization of agriculture in the fertile lands drained by the River Mara—the play of policy in pastoralism (Sindiga 1984). These conditions notwithstanding the lions, as apex predators, succumb to pressure from changing territorial lands and shrinking prey populations. This lays foundations for the examination of the habitability of lions in these lands with reference to present physical conditions (Bauer et al. 2015).

Microclimatic influences

The microclimate of a region, referenced within a scale of tens of metres, is unique to a particular area under consideration, being affected by physical parameters like air temperature, relative humidity, solar insolation flux, wind speed, and wind direction (Oke 2002). Entrenched localized effects brought about by soil parameters like moisture, thermal gradient, temperature, and topography influence the microclimate also (Shirley 1929, p. 1945). These effects on lions at the Masai Mara National Reserve can be ascertained on the basis of wildlife habitat selection as influenced by microclimates (Perry 1994). The monitoring of structural changes in landscape and their altered ecological processes is possible at multiple spatial scales (Chen et al. 1999). We now give some concrete examples. There are many species of Acacia trees that are present in the grass-dominated savannah each slightly differing in appearance, and which alter the microclimate in their immediate environment along with other exotic species (Table 1) through the effects of tree canopies against open grasslands (Belsky et al. 1989). The whistling acacia (*Vachellia drepanolobium*) possesses black thorns with bulbous bases and is known for housing ants (*Crematogaster nigriceps*) in a symbiotic relationship. The iconic umbrella thorn acacia (*Vachellia tortilis*) grows in arid conditions and is known for its high tolerance of alkalinity. The yellow-barked acacia (*Vachellia xanthophloea*) grows in slightly wetter regions. The presence of differing tree canopy, in turn, modulates the air flow patterns in the lowest part of the atmospheric boundary layer.

Table 1 Scientific and common names of grasses, trees, and shrubs

Scientific name	Common name
Themeda triandra	Red oat grass
Hyparrhenia hirta	Thatch grass
Vachellia tortilis	Umbrella thorn acacia
Diospyros abyssinica	Giant diospyros
Vachellia drepanolobium	Whistling acacia
Vachellia xanthophloea	Yellow-barked Acacia
Euphorbia ingens	Candelabra tree
Ficus sycomorus, *Ficus thonningii*	Fig trees
Kigelia africana	Sausage trees

Boundary layer characteristics

The Masai Mara is primarily “open grassland”. The terrain spans an expansive area spotted by trees, shrubbery, and thickets, though for the most part, the land is evenly covered by grass. The lowermost region of the atmosphere, having the most dynamic and direct interaction with the land, is termed the atmospheric boundary layer. Boundary layer flow can be markedly different from region to region, greatly influenced by the topography of the terrain with the presence of plant canopies and variation of insolation (Bitsuamlak et al. 2004; Belcher and Hunt 1998; Raupach and Thom 1981; Cionco 1965; Mahrt 2000). Most often during the day, the land heated by solar radiation drives convection through buoyant thermal plumes, which follows from the simplest flow instability mechanism of a lighter fluid (that heated by the surface) underlying a heavy fluid (that relatively further above the surface). This causes temperature changes within the boundary layer over differing time durations. It is worth noting that even with air temperature changes and associated anomalies, one observes persistent long-range power-law correlations for time scales longer than about four months and shorter than about six years. This suggests that the temperature fluctuations over small time periods (i.e. a few months) are related to those over longer time periods (i.e. a few years). In this sense, the cats can feel such temperature changes over isolated thermal episodes as well as over seasonally (Efstathiou and Varotsos 2010). Temperature changes cause the boundary layer to grow and also act as a constant source of energy for sustaining turbulence. Turbulence is a flow feature characterized by a mixing of the flow properties across various length and time scales, where eddying motions of different sizes overlap and influence each other. This mixing ensures a uniform distribution of physical properties like temperature, moisture, and humidity in the boundary layer—the crucial metrics for comfort. For instance, a thicket or dense undergrowth in the forest floor could well

Table 2 Land use and soil type categories

Number	Land use category	Number	Soil type category
1	Evergreen needleleaf forest	1	Sand
2	Evergreen broadleaf forest	2	Loamy sand
3	Deciduous needleleaf forest	3	Sandy loam
4	Deciduous broadleaf forest	4	Silt loam
5	Mixed forests	5	Silt
6	Closed shrublands	6	Loamy
7	Open shrublands	7	Sandy clay loam
8	Woody savannas	8	Silty clay loam
9	Savannas	9	Clay loam
10	Grasslands	10	Sandy clay
11	Permanent wetlands	11	Silty clay
12	Croplands	12	Clay
13	Urban and built-up	13	Organic material
14	Cropland/natural vegetation mosaic	14	Water
15	Snow and ice	15	Bedrock
16	Barren or sparsely vegetated	16	Other (land-ice)
17	Water		
18	Wooded tundra		
19	Mixed tundra		
20	Barren tundra		

act as an obstacle to the dominant wind, creating a damp and humid zone in the wake region. This might be a favourable or unfavourable condition based upon what is comfortable for a given animal species—which might then tend to seek or avoid such locations. The vertical structure of the atmospheric boundary layer over the grassland can be expected to follow a diurnal cycle—with a convection-driven unstable boundary layer growth during the day, followed by a stable boundary layer at night (Stull 1988). For the most part, the turbulent

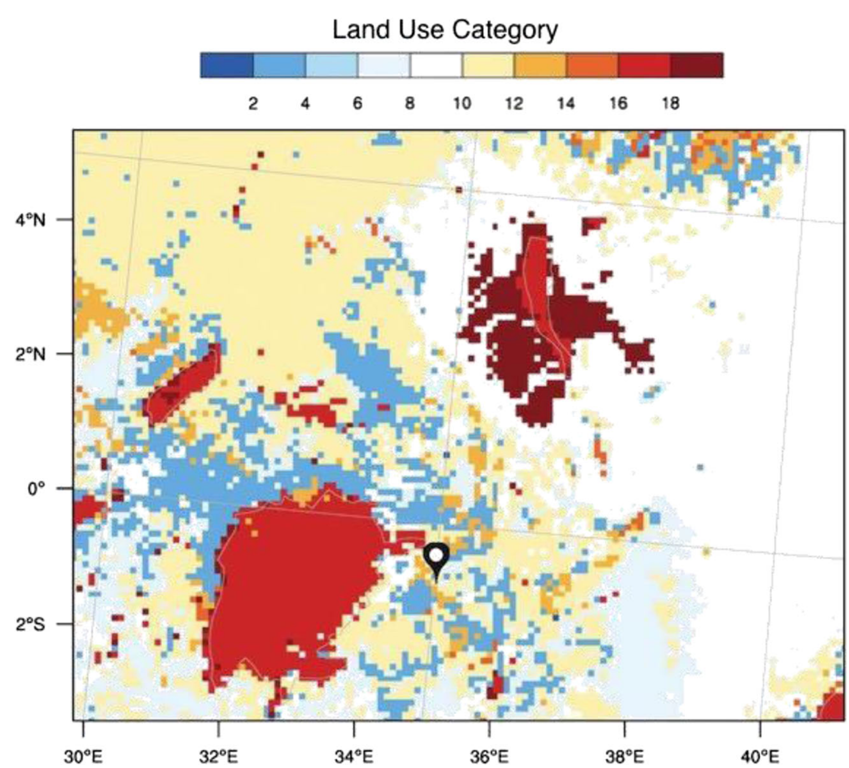

Fig. 1 Masai Mara National Reserve marked in the map shows MODIS land use categories between 10 and 12 (in accordance with Table 2), pertaining to grasslands, permanent wetlands, and croplands

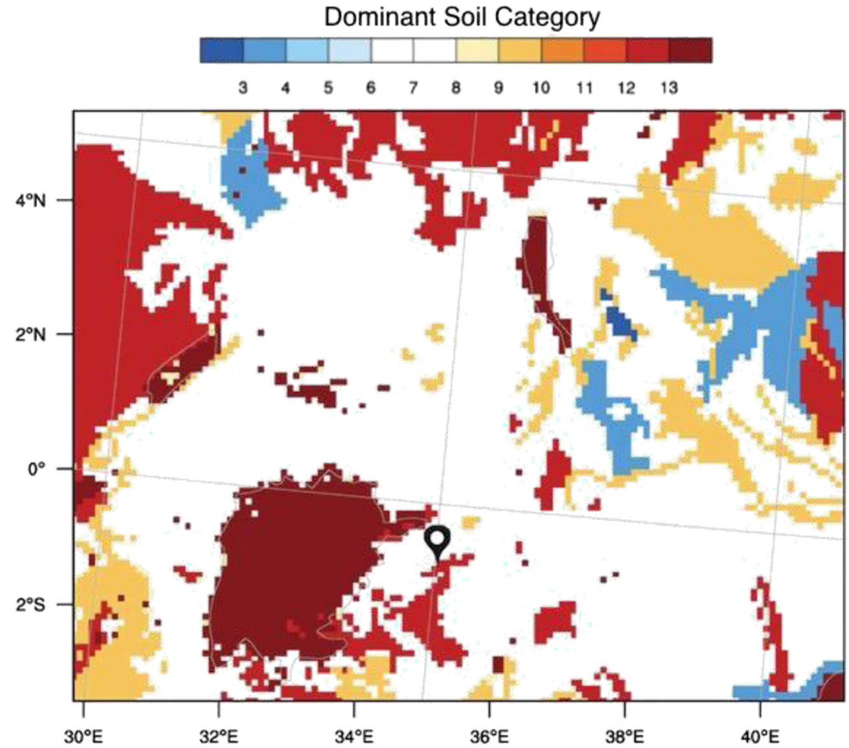

Fig. 2 The soil categories in the Masai Mara range from soil types 5 to 7 (in accordance with Table 2), pertaining to silty, loamy, and sandy clay loam

boundary layer (up to approximately 1.5 km above the ground) will be sufficiently well mixed. Some terrain-induced heterogeneities in the flow can occur, which might be a result of a gradient in surface heating due to a gradient in the surface material (transition from grass covered to barren surface), or undulations in the terrain height, channeling the flow close to the surface (Jackson and Hunt 1975; Britter et al. 1981).

Dust devils and whirlpools also form regular features of airflow in such areas. Thus, the spatial distribution of the wind

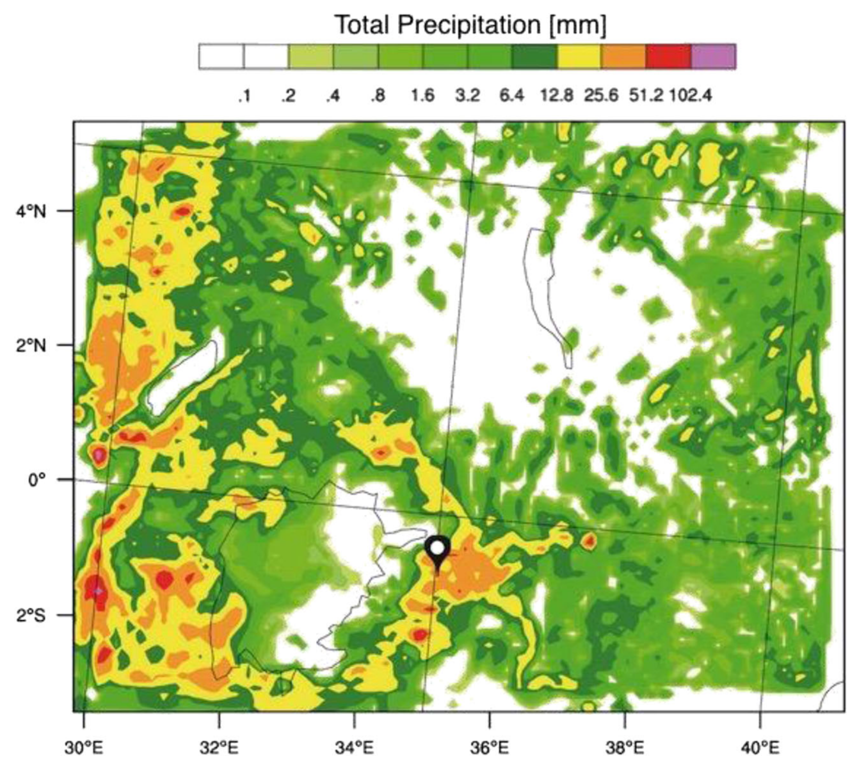

Fig. 3 Masai Mara witnesses precipitations ranging between 6 and 12 mm during the month of March. East Africa experiences pre-monsoon showers in this period

is crucially important—it is after all the only carrier fluid that transports temperature and moisture from locate to locale, directly affecting the levels of comfort felt by an organism.

Predicted mean vote

Every organism displays a commonality in the form of metabolism. The metabolic activity regulates functions of the body right from the cellular level of organization to other functions. The external environment plays a direct role in the determination of metabolic activity, resulting from the physical parameters of humidity and temperature. The *predicted mean vote* or PMV is a measure of the comfort level in a human that relates the internal metabolic rate and the heat loss to the environment (Fanger 1972); it aims at optimizing the ambient physical parameters like the air velocity, humidity, and the mean radiant temperature with the insulation and basal metabolic rate of the individual in that very setting. The ascertainment and rating of the PMV according to a 7-point scale of thermal comfort results in a gradation from − 3, perceived as very cold, to + 3, perceived as very hot, through 0, perceived as neutral (Table 3) (ASHRAE 2004). By the definition of comfort as "that condition of mind which expresses satisfaction with the thermal environment", the importance in its evaluation with respect to the external factors in the environment includes atmospheric variables (BS EN ISO 7730: 1995). Thermal sensitivity of an individual plays a significant role in behavioural and physiological adaptability to the environment—the sensation and level of thermal discomfort are synonymous, leading to thermal perception as a psycho-physiological response (Auliciems 1981). The big cats and humans share the mammalian attributes of being warm blooded and possess a four-chambered heart, in addition to the presence of a comparable number of limbs that aid in movement and organs that result in the shared functions of respiration, digestion, circulation, and excretion. The biological understanding of our common features and the principle of the PMV are extended to analyse the thermal comfort of lions in their natural habitat at the Masai Mara National Reserve. With this in perspective, the aforementioned table (Table 2) can be appreciated and serve as a ready reckoner for the PMV for the lions too—all the negative numbers associated with a PMV value would still feel chilly while the positive ones would feel warm—perhaps the lions would feel the warmth more acutely than the coolth. Hence, + 3 would be unbearable for the lions while the humans would just about be able to bear the torrid heat of the tropics. The PMV is numerically ascertained by equations that accommodate a range of skin temperatures that sensitise the body through evaporation of sweat as a result of the internal body metabolism and external heat loads. According to Fanger, this is correlated with six primary variables, namely, air temperature, mean radiant temperature, air velocity, vapour pressure, clothing factor, and metabolism. It must be noted that the original paper was drafted for human comfort. However, as stated earlier, lions are warm-blooded animals and hence bear

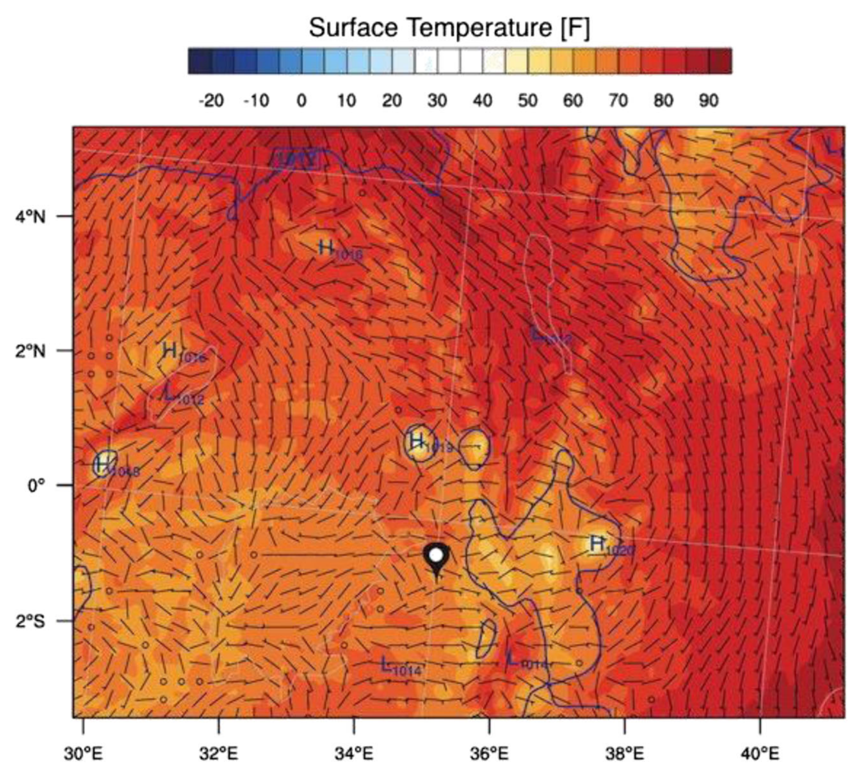

Fig. 4 Masai Mara has surface temperatures between 50 (10 °C) and 60 °F (15.55 °C) for the month of March

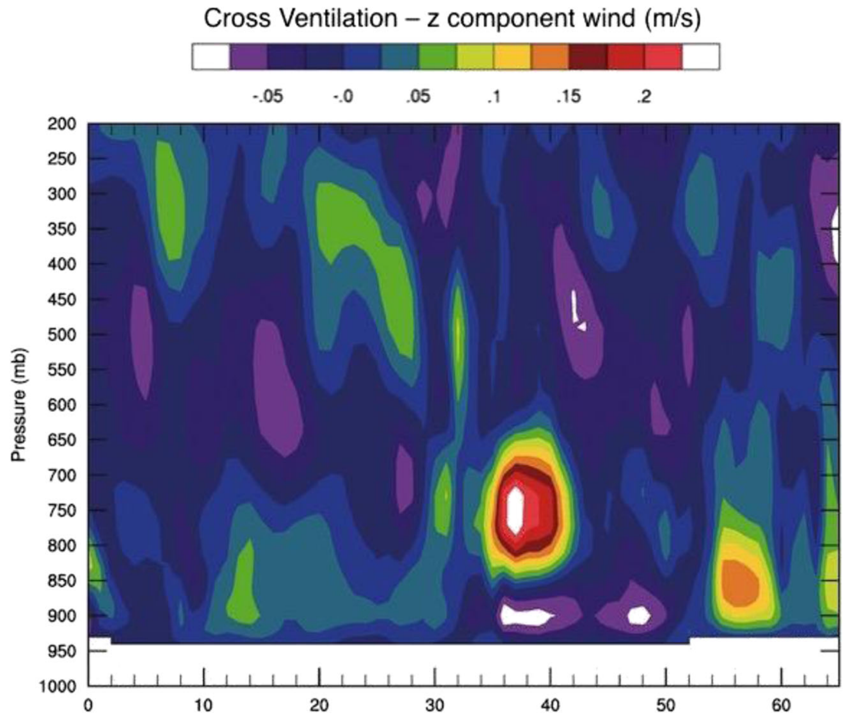

Fig. 5 A cross section of the vertical velocity variations over the entire reserve covering the lowest surface layer shows the layer-averaged highest vertical wind velocity over Masai Mara as 0.05 m/s

resemblance to humans. Therefore, an attempt is made to rescale the findings towards lion comfort and the first obvious step would be to quantify the main meteorological variables that characterize the boundary layer of the habitat concerned.

Use of computational fluid dynamics in quantifying comfort levels in the Mara

In recent years, meteorologists are observing a trend to move away from large multifunctional Earth-observing satellites to

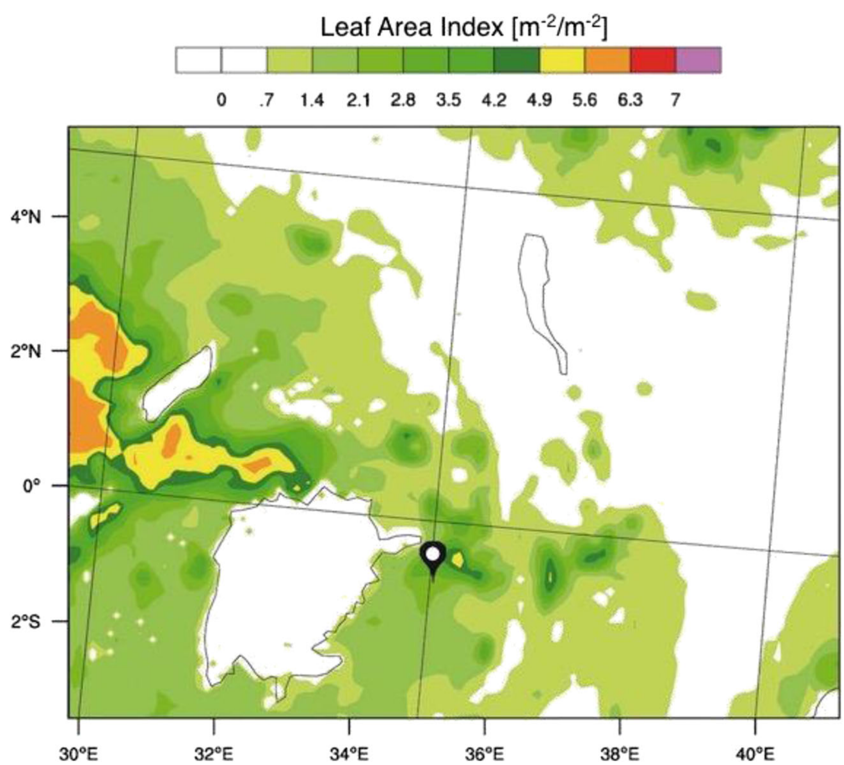

Fig. 6 The Leaf Area Index (defined as the fraction of the ground covered by leaves over the total ground surface area) ranges between 4 and 5 over the Masai Mara, testified by the dry grasslands with dull shades of yellows and browns

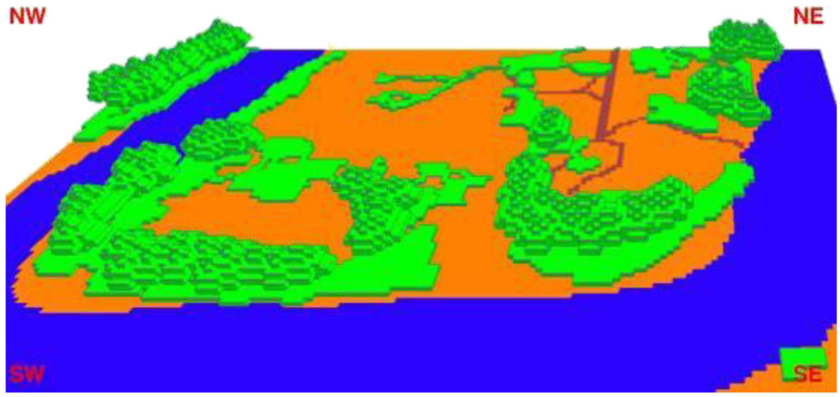

Fig. 7 Area Input file for ENVI-met showing the terrain, vegetation, and hydration in the region under study, defined by the coordinates [1.3246° S, 35.0120° E], [1.3234° S, 35.0124° E], [1.3250° N, 35.0123° E], and [1.3242° N, 35.0130° E]. This file is simulated for the simulated time for carrying out the calculations of PMV

smaller ones dedicated to specific observational tasks with obvious advantages. These include simple and speedy designs, a quicker manufacturing time line, many more launch opportunities, and low costs involved among others. Additionally, smaller satellites lend easier access to derived retrievals because the likelihood of differing instrument requirements is minimized. In addition, one also has the added advantage of risk reduction. For all these reasons, smaller satellites provide opportunities for developing countries to get involved in technology transfer with the development of indigenous space-related capabilities useful to many stakeholders (Cracknell and Varotsos 2007).

The Moderate Resolution Imaging Spectroradiometer (MODIS) provides a bird's eye feel for the overall land use and soil type categories (Table 2), which have their telltale signature on soil temperature, surface air temperature, strength of the wind vectors, strength of the updrafts, and thermals. All these are interconnected and affect comfort levels that are prescribed by the PMV. The corresponding images (Figs. 1, 2, 3, 4, 5, and 6) were obtained by running the state-of-the-art Weather Research and Forecasting (WRF) model for the month of March 2015 by sourcing six hourly satellite data—0.5° resolution gridded Global Forecast System (GFS) data (Michalakes et al. 2001). This was obtained from the National Centre for Environmental Prediction (NCEP) NOAA Port (National Oceanic and Atmospheric Administration) satellite. The WRF model used this data for solving the full Navier-Stokes equations incorporating boundary layer characteristics and the cloud cover. Additionally, all the meteorological parameters—pressure, temperature, total moisture, u, v, and w components of the wind speeds—are incorporated along with an accurate prescription of the

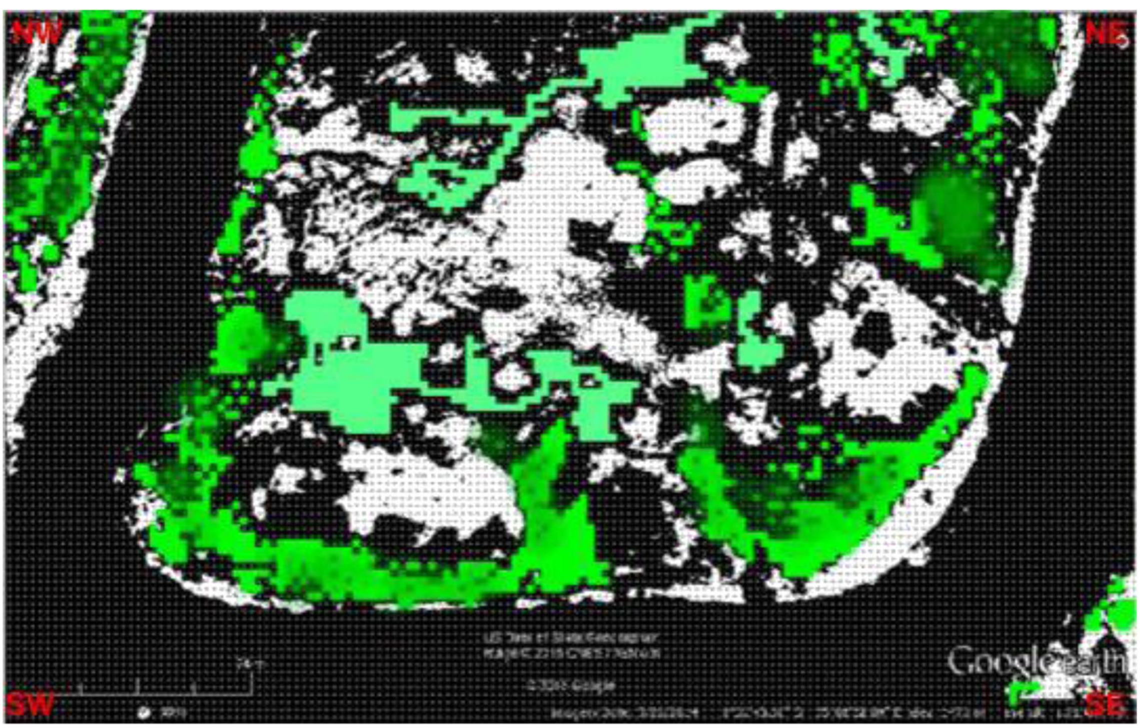

Fig. 8 Vegetative attributes of the studied region, ranging from trees to shrubs and grass, presented as a bitmap overlaid with Google Earth™ image

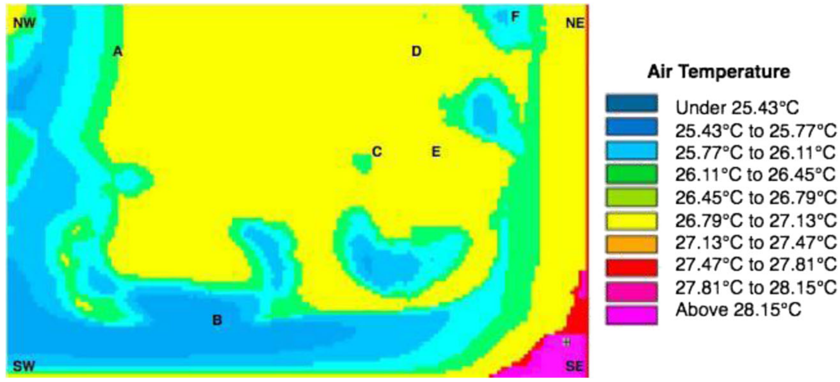

Fig. 9 Profile of air temperature for the region studied—the dominant values are referenced using the points "A", "B", "C", "D", and "E". Air temperature is lowered under the influence of hydration. This is illustrated through "B", lying on the shore with shrubs, receiving the shade from canopies and hydrated by the River Mara, in accordance with Robitu et al. (2006)

boundary layer turbulence. The study used the k-ε model to characterise boundary layer turbulence. Solar insolation data was also sourced from satellites that drive the diurnal variation of the boundary layer height. WRF double-moment scheme for cloud microphysical characterization was switched on for the sequences shown.

The information sourced from the WRF model, spanning hundreds of kilometres, was subsequently downscaled to a few hundreds of metres in order to configure a smaller microclimatic model. The use of high-resolution microclimate modeling system like ENVI-met Version 4 makes it possible to ascertain comfort levels that are numerically rendered by incorporating the principles of CFD and applied mathematics (Fanger 1972; Huttner and Bruse 2009). It is possible to generate vivid images of the local environment and the outdoor microclimate by understanding the impact of topography, vegetation, hydration, sunlight, and anthropogenic influences. Fluid flows and bioclimatology are quantified by simulating areas of interest replete with the aforementioned entities with reference to soil physics, atmospheric dynamics, and vegetation response. The physical parameters like satellite and weather data are used while designing the area to simulate the area as input for a required period of time and the CFD code returns profiles of atmospheric variables and PMV as outputs, indicating the gradients through different shades. Using the aforementioned model, a region in the Masai Mara was modeled as an Area Input (Fig. 7). The following coordinates are used: [1.3246° S, 35.0120° E] at the top-left, indicated by the northwest (NW) direction; [1.3234° S, 35.0124° E] at the top-right, indicated by the northeast (NE) direction; [1.3250° N, 35.0123° E] at the bottom-left, indicated by the southwest (SW) direction; and [1.3242° N, 35.0130° E] at the bottom-right, indicated by the southeast (SE). This region is of a classic grassland setting, with interspersed shrubs and grass, a country road used for wildlife tourism, and is flanked by the meandering River Mara on three sides. The vegetative attributes as a bitmap are overlaid with a Google Earth™ image of the region (Fig. 8). The time chosen for simulation was during midday and afternoon, the most probable time of maximum discomfort—as they are the hottest hours—referenced for the months of February and March 2015. The body parameters of body weight (as a cub weighing 100 kg), height (1 m), clothing insulation (0.8 taken as fur of lion), and metabolic rate (94.58 W) were used as inputs to predict the PMV using this model.

Results

We now show explicitly the expected PMV values over many sensitive locales of interest.

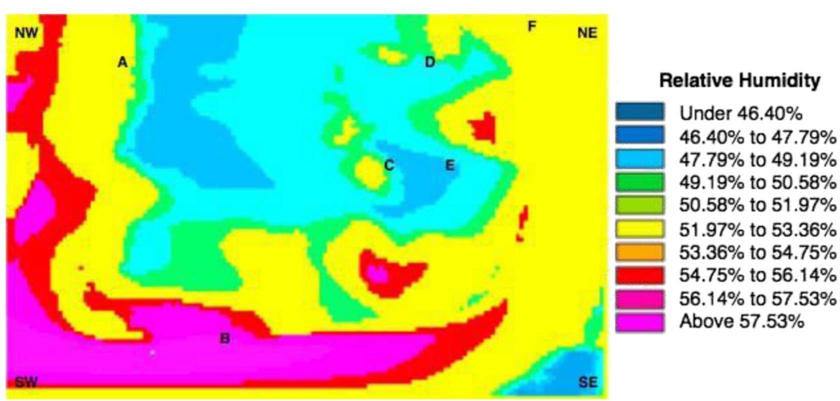

Fig. 10 Profile of relative humidity illustrates the maximum values in regions that are highly hydrated by the drainage of River Mara—"B" shows a value higher than 57%

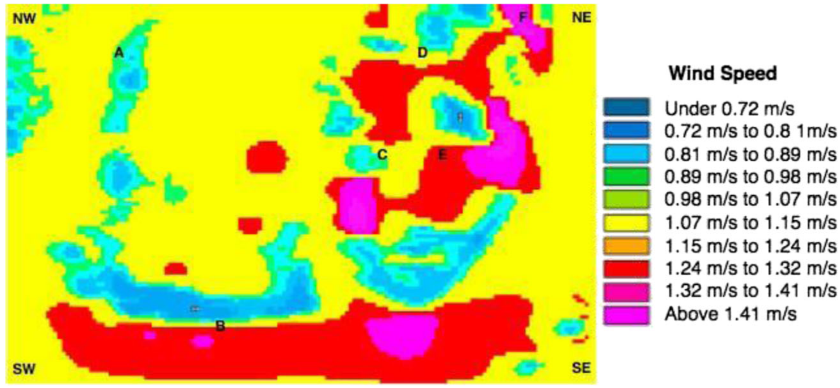

Fig. 11 Profile of wind speed shows regions appearing as shielded areas with shrubs as obstructions ("C", 0.94 m/s) to open spaces ("B" and "E", 1.28 m/s), in accordance with the relation between wind velocity and surface roughness provided by Oke (2002)

The results of these simulations pictorially profile the main atmospheric variables along with the PMV. Specific points are chosen in the profiles of the region, to characteristically represent the vegetative attributes of the selected area and its landscape. This ranges from A (on shore with grass), B (on shore with shrubs), C (inland with shrubs), D (inland on a country road), E (inland without grass), and F (slightly inland with grass and shrubs), as shown in the distribution of air temperature, relative humidity, wind speed, mean radiant temperature, and PMV. The effect of vegetation, through the provision of shade, is a good means of moderating thermal comfort to assuage the effect of solar radiation (Berkovic et al. 2012). In addition, the reduction in air temperatures through evapotranspiration by leaves and the presence of wet surfaces on the ground are evidenced by the evaporative cooling of air (Axarli and Chatzidimitriou 2012). The combined phenomena of evaporation and evapotranspiration between water, vegetation, and air immensely regulate the outdoor thermal environment by cooling the air (Robitu et al. 2006; Nishimura et al. 1998). The air temperature pattern (Fig. 9) illustrates "A" with a temperature of approximately 26 °C, "B" (25 °C), and "E" (27 °C), revealing the effect of hydration on lowering the air temperature—"B", lying on the shore with shrubs, receives the shading from canopies and is hydrated by the River Mara. It is tacit that the relative humidity (Fig. 10) is at its maximum in regions that are highly hydrated—"B" shows a value higher than 57%. Wind speed, though in increment from shielded areas with shrubs as obstructions ("C", 0.94 m/s) to open spaces ("B" and "E", 1.28 m/s) (Fig. 11), is in accordance with the relation between wind velocity and surface roughness provided by Oke (2002) although the contribution of wind to assuage comfort is limited, according to Berkovic et al. (2012). The profile of mean radiant temperature (Fig. 12) is starkly represented through its high values in spaces bereft of vegetation, with open spaces valued at above 55 °C, with a temperature difference as high as 10 °C in comparison with some vegetated regions. The effect of the atmospheric variables is seen in the values of PMV (Fig. 13)—"B" appears most comfortable in the given setting with a PMV of 1.9, owing to the combined effect of the canopy and hydration as opposed to "E" with a PMV of 2.82. The effect of the canopy as opposed to mere grass is illustrated by the difference in "A", with a mid-range PMV value of 2.3 as opposed to "B", located slightly inland and away from the water. "F" shows the effect of hydration with a slightly higher (0.5 units) PMV of 1.95 as opposed to the lower PMV registered in "B". The values are listed in Table 3.

Wider implications

The surveyed region is only an investigatory area, used as a pilot project for attempting a study of comfort and habitability of lions in their natural habitat worldwide. In this sense, the

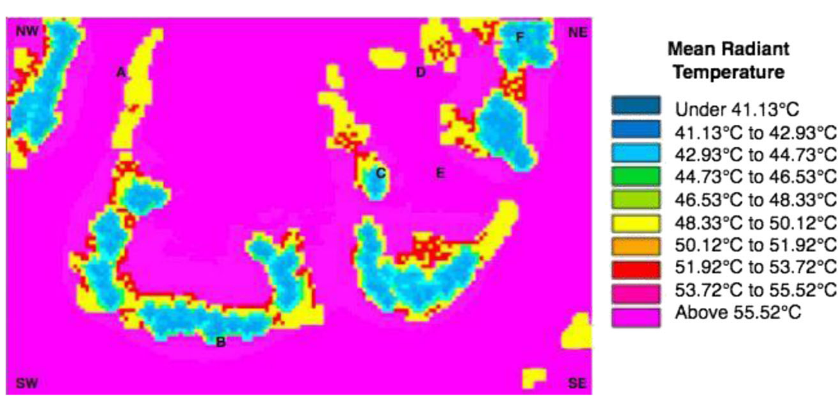

Fig. 12 Profile of mean radiant temperature shows that high values occur in spaces bereft of vegetation, with open spaces valued at above 55 °C, with large temperature differences in comparison with some vegetated regions

Fig. 13 Profile of predicted mean vote (PMV) shows the effect of the atmospheric variables as "B" appears most comfortable in the given region with a PMV of 1.9, with the effects of canopies and hydration, as opposed to "E" with a PMV of 2.82. The effect of the canopy—providing shade—as opposed to mere grass is illustrated by the difference in "A", with a mid-range PMV value of 2.3 against "B"; located slightly inland and away from the water, "F" shows the effect of hydration with a slightly (0.5 units) higher PMV of 1.95 in comparison to the lower PMV registered in "B"

present study is exploratory but provides suitable pointers for undertaking further studies using the power of CFD. The effects of changing landscapes in game reserves, as detailed by Homewood et al. (2001) and Ogutu et al. (2009), are witnessed at the microclimatic level through the analysis of fluid flows vis-à-vis flora and fauna in the Mara ecosystem. The effects of overexposure of lions to solar radiation are evident in high mean radiant temperatures (> 55 °C) due to the lack of suitable canopies and result in unbearable PMV values between 2 and 3, falling in the range from being hot to very hot. Such high MRTs will have a profound effect on the energy budget of an animal's thermal comfort, which was explored in this study primarily in terms of very detailed estimates of atmospheric variables. Lions adapt to temperature surges and resort to panting and wetting the skin when there is a water pool around. Our marked zones A, B, C, D, etc. may well serve as ready reckoner for future conservationists who can have a foreknowledge of areas that are likely to be moist and hydrated under changing atmospheric conditions. The procedure outlined (the use of WRF simulations coupled with ENVI-Met PMV categorizations) will be far more reliable than using analytical calculations. Convective heat losses are naturally minimized by the lions owing to the high insulation afforded by their furry coats.

Table 3 ASHRAE-prescribed PMV scale

+ 3	Hot
+ 2	Warm
+ 1	Slightly warm
0	Neutral
− 1	Slightly cool
− 2	Cool
− 3	Cold

In addition to the direct anthropological influences resulting in the decline in lion populations, the overall high PMV testifies the inhabitability of the region, as experienced by these animals. In view of efficient landscape management, climate change, though uncertain in its impacts, is projected to exacerbate increases in temperature (2.5 to 3.5 °C), necessitating land management strategies to enhance aquifer recharge of the principal source of water in such regions. This study has shown that even at the current stage, the PMV values and the mean radiant temperatures are uncomfortably high. This might perpetuate animal movement away from their original locales. Deforestation brought about by the desiccation of natural habitats, as detailed by Ogutu et al. (2009), leads to the lack of vegetative cover, altering microclimates and decreasing canopies according to Belsky et al. (1989), Berkovic et al. (2012), and Young et al. 2013. This can have significant consequences. Lions spend a lot of their time during a day by simply lying down. When this happens on denuded substrates, conduction between the animal and the substrate affects their energy budget. The amount of heat loss or gain will be affected by the surface thermal properties, specifically its *U*-value or thermal transmittivity (Oke and Cleugh 1987). Also, on a microclimatic scale, other anthropogenic influences may include higher vehicular movement with more roads within the reserve, resulting in heat islands. This may be combated using suitable green roof-like models for mitigation (Santamouris 2014). The mollification of the environment to suit thermal comfort for lions is hence the key to the comfortable survival of this species with the provision of habitable spaces within natural reserves. The high PMV values in the surveyed region provide evidence for the status of lions as being regionally endangered (Bauer et al. 2015). This was achieved through the novel incorporation of fluid flow-mediated comfort index calculations.

Acknowledgements This research was conducted after a personal visit to the Masai Mara National Reserve, organized by Mr. Binod Sharma at the United Nations in Nairobi. The authors humbly thank VIT University, Vellore, India, and University of Leeds, UK, for making this research possible and for providing an intellectual space for the betterment of wildlife conservation. The Masai people are sincerely thanked for the upkeep and maintenance of their natural heritage and are held in reverence. Thanks are also due to Mr. Siddharth Gumber.

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