THERMODYNAMIC ASSESSMENT OF THE IMPACT OF THE CLIMATE CHANGE ON HONEYBEES

by

Cennet Yıldız

Submitted to Graduate School of Natural and Applied Sciences
in Partial Fulfillments of the Requirements
for the Degree of Master of Science in
Chemical Engineering

Yeditepe University
2018

THERMODYNAMIC ASSESSMENT OF THE IMPACT OF THE CLIMATE CHANGE ON HONEYBEES

APPROVED BY:

Prof. Dr. Mustafa Özilgen ....
(Thesis Supervisor)

Prof. Dr. Levent Kurnaz M. Levent KURNAZ

Assist. Prof. Dr. Levent Organ ....

DATE OF APPROVAL: ..../..../2018

ACKNOWLEDGEMENTS

I am grateful to my supervisor, Prof. Dr. Mustafa ÖZİLGEN, whose expertise, understanding, generous guidance and support made it possible for me to work on this topic. He helped me complete this work by supporting me during the work and he motivated me persevere with my work.

I am also thankful to my parents for their endless love and their encouraging every time in my life and I would like to thank my friends for their supporting morally.

ABSTRACT

THERMODYNAMIC ASSESSMENT OF THE IMPACT OF THE CLIMATE CHANGE ON HONEYBEES

Honeybees are among the most sensitive biological species to the changes in environmental conditions. Since pollination is necessary for the cultivation of more than 75 per cent of the crops used directly by the people worldwide, any injury to the honeybee population due to the climate change may jeopardize the food security. Therefore, thermodynamic parameters which are implemented on the honeybees under the prevailing environmental conditions and which may be implemented in the case of an anticipated temperature change are assessed. Work performance and entropy generation by the honeybees while resting, foraging for nutrients outside of the hive and fanning the hive are assessed based on sucrose metabolism. The minimum entropy generation accounted was 1.2 x10^{-7} W/g honeybee K while the 1-7 h old young honeybees were resting under atmospheric pressure with 0.5 M of sucrose supply at 15 μl/min flow rate in the hive. The maximum entropy generation, 7.2 x10^{-5} W/g honeybee K, was accounted during foraging at 35°C at shade with 0.5 M of unlimited sucrose supply. With 3,000 honeybees, work performance was 3.17 kJ/kg dry air, heat generation was 4.44 kJ/kg dry air and the entropy generation is 161.6 W/g honeybee K while raising the temperature of the hive by 1°C. On the other hand, they have to perform 4.5 kJ/kg dry air of work, generate 7.27 kJ/kg dry air of heat and 308.9 W/g honeybee K of entropy to reduce the temperature of the hive by 1°C. The results show that during cooling by 1°C the honey bees performed 1.4 folds of work and generated 1.9 folds of entropy when compared to that of heating by 1°C, implying that global warming may create 90 per cent more entropy stress on the honeybees, when compared to that of a potential global cooling.

ÖZET

BAL ARILARI ÜZERİNDE İKLİM DEĞİŞİKLİĞİNİN ETKİLERİNİN TERMODİNAMİK DEĞERLENDİRMESİ

Bal arıları çevresel koşullardaki değişimlere en hassas biyolojik türler arasındadır. Dünya genelinde doğrudan insanların kullandığı ekinlerin yüzde 75'inden fazlasının yetiştirilmesi için tozlaşma gerekli olduğundan, iklim değişikliğinden dolayı bal arısı popülasyonununda meydana gelecek herhangi bir zarar, gıda güvenliğini tehlikeye atabilir. Bu nedenle, mevcut çevresel şartlar altında bal arılarını etkileyen ve ön görülen bir sıcaklık değişimi durumunda, bal arılarına etki eden termodinamik parametreler değerlendirilir. Dinlenme sırasında ve kovanın dışında yiyecek toplama ve kovanın havalandırılması süresince, bal arılarının iş performansı ve entropi üretimi sakaroz metabolizmasına dayanarak değerlendirildi. (1-7 saatlik) genç bal arıları kovanda 15 µl/dk akış hızında 0.5 M sakaroz kaynağı ile atmosferik basınç altında dinlenirken,minimum entropi üretimi 1.2 x 10^{-7} W/g bal arısı K olarak hesaplandı. Maksimum entropi üretimi 7.2 x 10^{-5} W/g bal arısı K, 0.5 M sınırsız sakkaroz akışı ile 35°C'de gölgede besin toplama sırasında hesaplandı. 3000 bal arısı ile, kovanın sıcaklığı 1^{o}C'ye yükseltilirken, iş performansı 3,17 kJ/kg kuru hava, ısı üretimi 4,44 kJ/kg kuru hava ve entropi üretimi 161.6 W/g bal arısı K. Diğer taraftan, kovanın sıcaklığını 1^{o}C azaltmak için, 4.5 kJ/kg kuru hava iş yapmak zorundadırlar,7.27 kJ/kg ısı ve 308,9 W/g bal arısı K entropisi üretmelidirler. Sonuçlar, 1^{o}C'de soğutma sırasında, bal arılarının 1.4 kat iş yaptığını ve 1^{o}C'de ısıtma ile karşılaştırıldığında 1.9 kat entropi ürettiğini ve küresel ısınmanın, potansiyel bir küresel soğumayla kıyaslandığında, bal arılarına yüzde 90 daha fazla entropi stresi yaratabileceğini göstermektedir.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS/ABBREVIATIONS

A	Surface area of thorax
Δfh°	Standard enthalpy change
D	Characteristic dimension of the body part
h^{-}	Specific enthalpy at standart condition
h^{-}	Specific enthalpy at standart condition
$h^{-\circ}$	Specific enthalpy at 310 K
h_{in}	Specific enthalpy of substances up take by the honeybee
h_{out}	Specific enthalpy of substances produced by the honeybee
h_{thorax}	Convection heat transfer coefficient
$L\downarrow$	Incoming long wave radiation
$L\uparrow$	Outcoming long wave radiation
m_{in}	Mass rate of substamces up take by the honeybee
m_{out}	Mass rate of substamces produced by the honeybee
η	Metabolic efficiency
Sn	Mol of carbon dioxide production or oxygen consumption
n_p	Mol of products
n_r	Mol of reactant
P	Pressure
Q	Convective heat transfer rate
R	Ideal gas constant
S	Mol of carbon dioxide production or oxygen consumption
T_a	Ambient temperature
T_{tho}	Thorax temperature
u	Internal enrgy of the honeybees
U	Air velocity
V	Volume of carbon dioxide production or oxygen consumption

W_{ATP}	Total work obtained from ATP molecules
W	Work generation during air ventilation

1. INTRODUCTION

1.1. ENVIRONMENTAL SUSTAINABILITY, GREENHOUSE GASES AND GLOBAL WARMING

Environmental sustainability may be described as a situation of resilience, interconnection, and balance that enables human society to fulfil its requirements without exceeding the capability of its assistant ecosystems and diminishing its biological diversity [1]. The greatest essential element of the environmental structure is biological diversity [2]. Under the prevailing environmental circumstances biodiversity is decreasing because of intense livestock farming, agriculture, and logging [3]. We may include the honeybees to the living beings which are negatively influenced by the changes occurring in the environmental infrastructure.

"*Greenhouse effect*" is among the major causes of the changes occurring in the environmental infrastructure and the subsequent global climate change. The trapping of heat by the greenhouse gases (GHG) such as carbon dioxide, methane, water vapor, ozone and nitrous oxide in the atmosphere causes that. The GHGs increase in the atmosphere by anthropogenic activities. They absorb heat radiated from the surface of the Earth and the lower atmosphere and then radiate majority of the energy back to the surface [4]. The natural processes, which might renovate the balance, take a long time compared to the rates at which human actions are interpolating CO_2 to the atmosphere and thus, the extra CO_2 from fossil fuel burning and destroying forest changed the balance of the carbon cycle. Consequently, human activities lead to amasses a substantial fraction of the CO_2 emission in the atmosphere and continue for thousands of years [5]. When concentrations of heat trapping greenhouse gases upsurge in the atmosphere, Earth's natural greenhouse impact causes the increase of the surface temperatures. NASA (2018)[6] estimates that the global surface temperature of the earth has increased by 1^{o}C between 1880 and 2016. The upsurge in the average global temperature; alters in cloud and precipitation mainly over land; glaciers and melting of ice caps and increases in ocean temperatures and ocean acidity because of absorption of carbon dioxide and heat by the seawater from the atmosphere and diminished snow cover [7]. In some circumstances, increases the yields or hotter weather increased amount of CO_2 could enables crop growth; while yields diminish above an optimum temperature that change by crop and crops fully-grown beneath high amount of CO_2 yield lack of nutrients like Zn, Fe, and protein. Moreover, hotter weather causes pests, weeds, and parasites to grow; extreme climate are often damaging to farmland, crops, and livestock the increasing ocean levels may erode and salinize the croplands [8].

1.2. THE TIMELINE OF GLOBAL WARMING

Climate change, global warming, and greenhouse gas emissions are among the most important issues, which affect environment negatively in the recent years. The climate change shows different effects. According to evidence, throughout earth’s history, various global climate changes, which were much higher than those inhabited in current, have occurred [9].

In the 1980s, according to the record written in ice cores, the earth had frequently experienced sudden and dramatic swings in temperature. Since then, a detailed picture of past 800,000 years has been put. There are significantly interrelation between temperature, CO_2 levels and sea levels: all rising and falling parallel each other, almost in lockstep [10]. Figure 1.1 represents that correlation between ocean surface temperature, sea level, greenhouse gas concentrations, and anthropogenic CO_2 emissions.

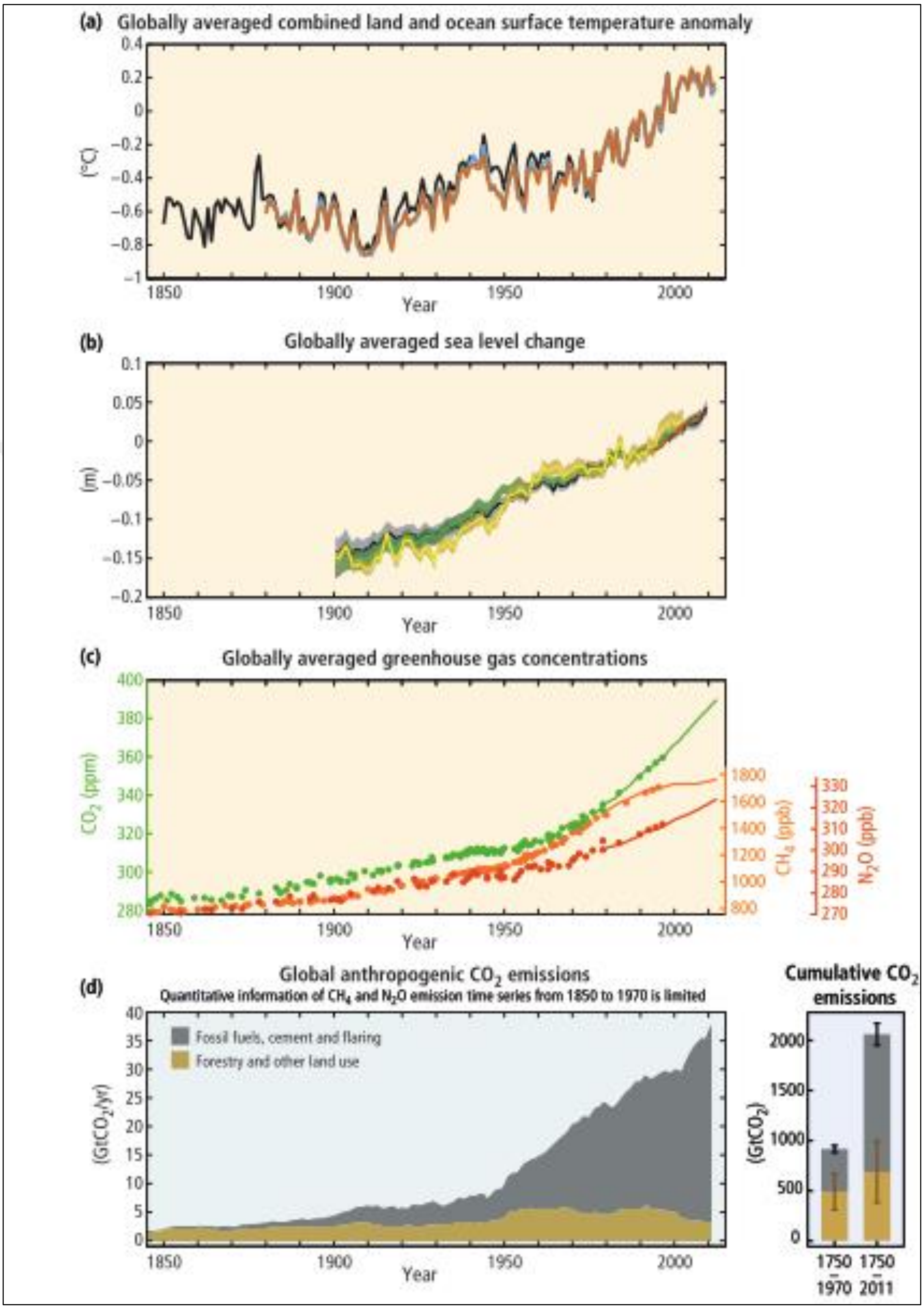

Figure 1.1. The complex correlation between the observations and the emissions. Observations: (a) According to the average over the period 1986 to 2005, ocean surface temperature variances and annually and globally averaged collective land. (b) According to

the average over the period 1986 to 2005 in the longest-running dataset, annually and globally averaged sea level change. Altogether datasets are settled as the similar rate in 1993 that is the first year of satellite altimetry data showed with red. (c) Atmospheric concentrations of the greenhouse gases such as N_2O with showed red, CH_4 showed with orange, and CO_2 showed with green. Indicators: (d) Global anthropogenic CO_2 emissions and cumulative emissions of CO_2 are displayed on the right hand side, as bars and whiskers, respectively. In panel c, the global impacts of the accumulation of CH_4 and N_2O emissions are represented. Greenhouse gas emission data which were obtained over the period 1970 to 2010 [11].

Mann *al. et* [12] have analyzed the spatiotemporal patterns of climate change over the past 500 years, and then took an pragmatic methodology to estimate the correlation between global temperature changes, differences in volcanic aerosols, solar irradiance and greenhouse-gas concentrations during the same period, using these statistically verifiable yearly global temperature reconstructions. In Figure 1.2, they have put forth the relationships of Northern Hemisphere mean (NH) temperature with three candidate forcing between 1610 and 1995.

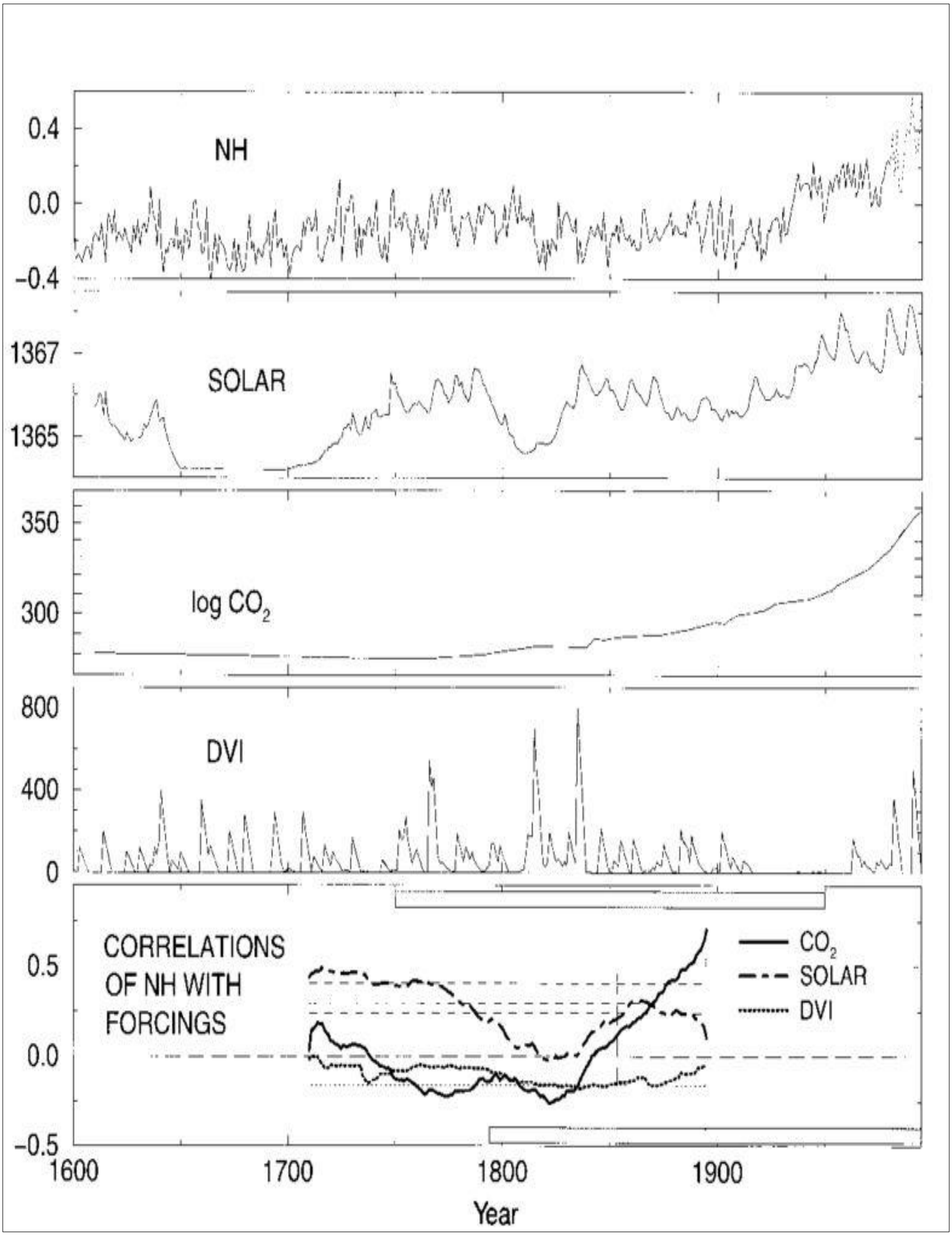

Figure 1.2. Relationships of Northern Hemisphere (NH) mean temperature with three candidate forcing between 1610 and 1995. Panels, as follows: 'NH', reconstructed NH temperature series, which were obtained between 1610 and 1980, updated with instrumental data, which obtained between 1981, and 95. 'Solar' indicates reconstructed

solar irradiance and atmospheric CO_2 measurements presents ‘log CO_2’, greenhouse gases. ‘DVI’ shows weighted volcanic dust veil index. Evolving multivariate correlation of NH series with the three forcing such as NH, Solar, and logCO_2 is represented by bottom panel. Horizontal dashed lines show one-sided (positive) 90 per cent, 95 per cent, 99 per cent meaning levels for correlations with solar irradiance and CO_2, while the horizontal dotted line show one-sided (negative) 90 per cent meaning threshold for connections with the DVI series. The gray bars display two difference 200-year windows of data, with the long-dashed vertical lines representing the center of the conforming window[12] .

According to records, global average temperature has enhanced at a rate of 0.70–0.75◦C per 100 years during 1910–2009. In other words, The Industrial Revolution has cause the earth to warm more than 0.8ºC. It means that we will have to face a serious condition where less than 1.2◦C warming is acceptable in the future, if 2◦C is higher than pre-industrial grade, which is a threshold of climate “safety”. In accordance with climate system concept, global temperature change and the alters of other climate system components (rise in the global average sea level, permafrost degradation and melting of ice and snow) eventuate global warming [13].

Even though there are many different records regarding earth surface temperature, the United Nations’ Intergovernmental Panel on Climate Change (the IPCC) history is most quoted. Two unrelated periods of warming are presented in Figure 1.3 and one of them approximately from 1910 through 1945 and another that started rather abruptly around 1975 and ended in 1998. The rates of warming of the two periods are statistically indiscernible [14].

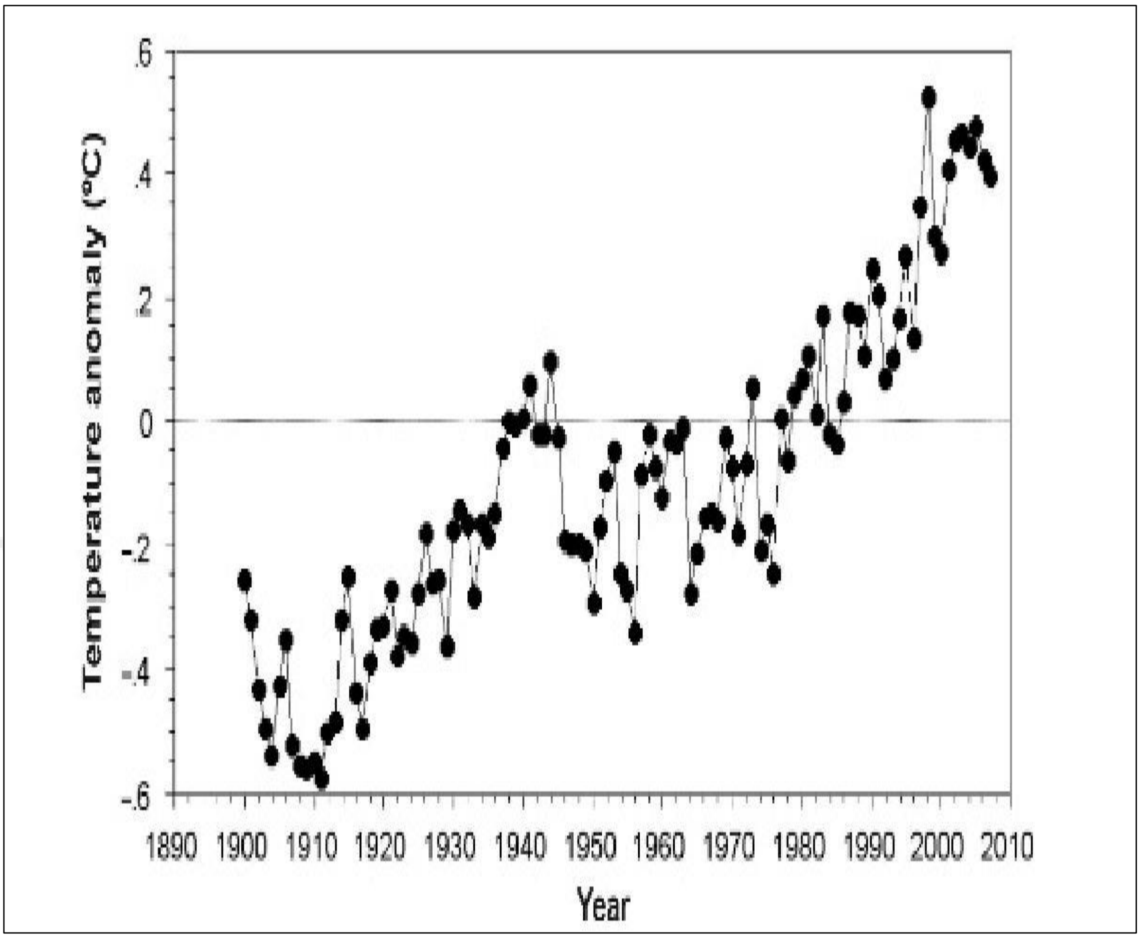

Figure 1.3. Average global surface temperature anomalies over the period 1900 to 2007 [14].

The spatial and periodic features of global temperatures variants support observationally the hypothesis of global warming depending on the upsurge of CO_2 in the atmosphere since the mid-20th. Besides, the increase of GHGs concentrations in the atmosphere forces climate models, therefore, it can reproduced climate warming over the past 30 years. Over the last hundred years, however, only the increase of concentrations drives climate models and they could not augment the warming in the 1940s and cooling in the period of 1950–1970 [15].

According to a global assessment of data since 1970 of IPCC [16], anthropogenic warming has had a visible impact on diverse physical and biological systems. Even though some are hard to distinguish because of conformation and drivers of non-climatic, other impacts of regional climate changes on natural human surroundings are evolving. However, more specific information related to a varied range of systems and lines about the nature of upcoming impacts, containing for some places not implicated in earlier valuations exists. sea Effects owing to changed periodicity and fierceness of phenomenal weather, sea level and, climate incidents have potential to alter. Some extensive climate incidents have significantly effects on environment, especially after the 21st century. The locations of important alters in data physical system over the period 1970-2004 are represented in Figure 1.4.

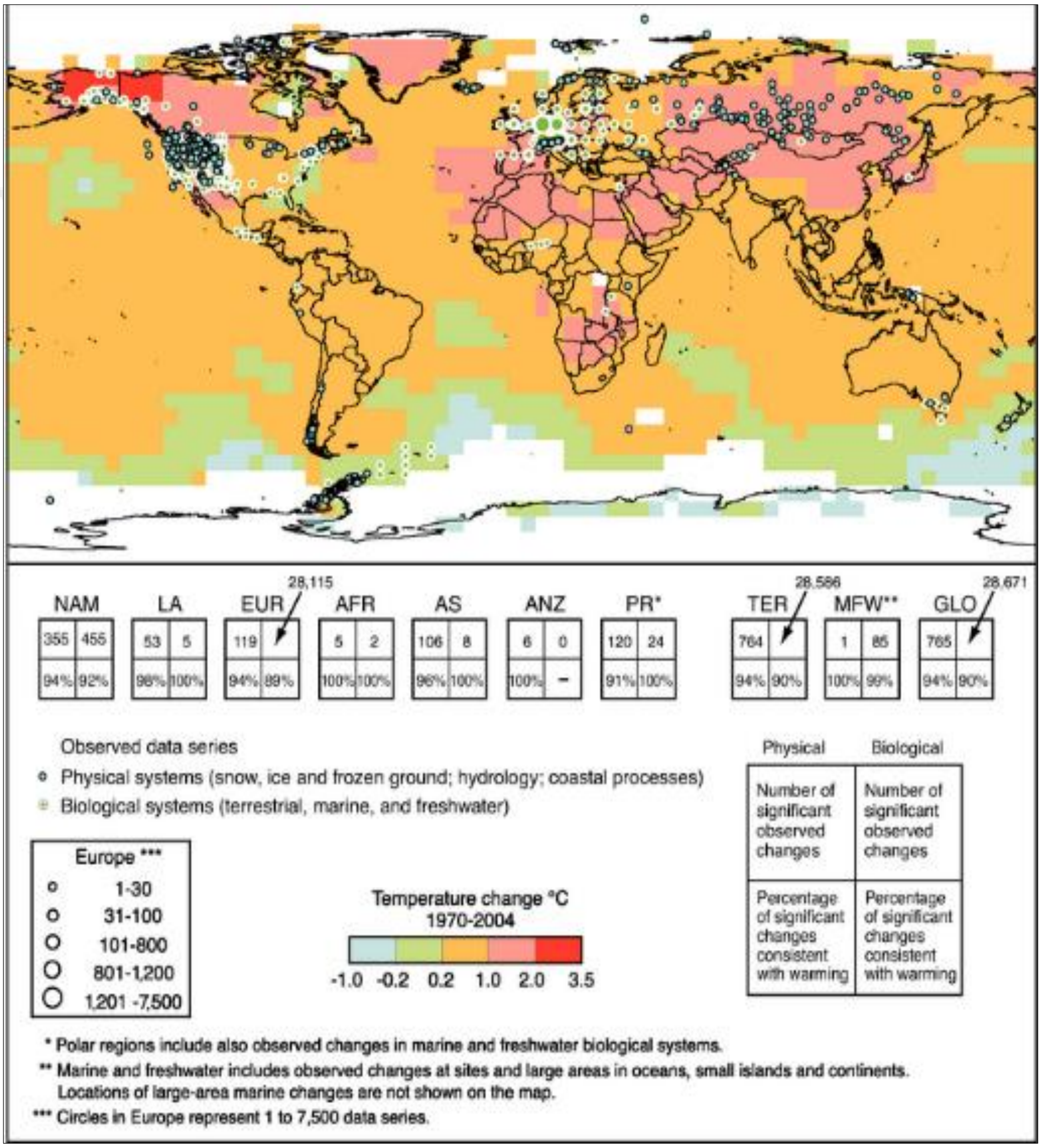

Figure 1.4. Locations of significant changes in data series of physical systems and biological systems, with surface temperature changes over the period 1970 and 2004. These encountered the next standards: (i) ending in 1990 or later; (ii) spanning a period of

at least 20 years; and (iii) displaying a major amendment in either aspect, as considered in individualistic studies. Enough observational climate data in order that a temperature tend are esitimated are not included by white parts. The total number of data series with meaning variations (top row) and the percentage of those consistent with warming (bottom row) is shown by the 2 × 2 boxes show for (i) continental regions: Latin America represented by LA , North America represented by NAM, Europe represented by (EUR), Asia represented by AS, Africa represented by AFR, Australia and Polar Regions represented by PR; and New Zealand represented by ANZ, and (ii) global scale: Global represented by GLO, Terrestrial represented by TER and Marine and Freshwater represented by MFW [17].

Although, before, the 20th century, impacts of global warming were well under control at the beginning of the current century, the situation got worsen. New industries and powerhouse resulted in the increase in impacts of global warming because they started operation and emitted dangerous gases, which cause the earth to heat up. Figures 1.5 and 1.6 shows the risks and impacts of global warming in years to come [18].

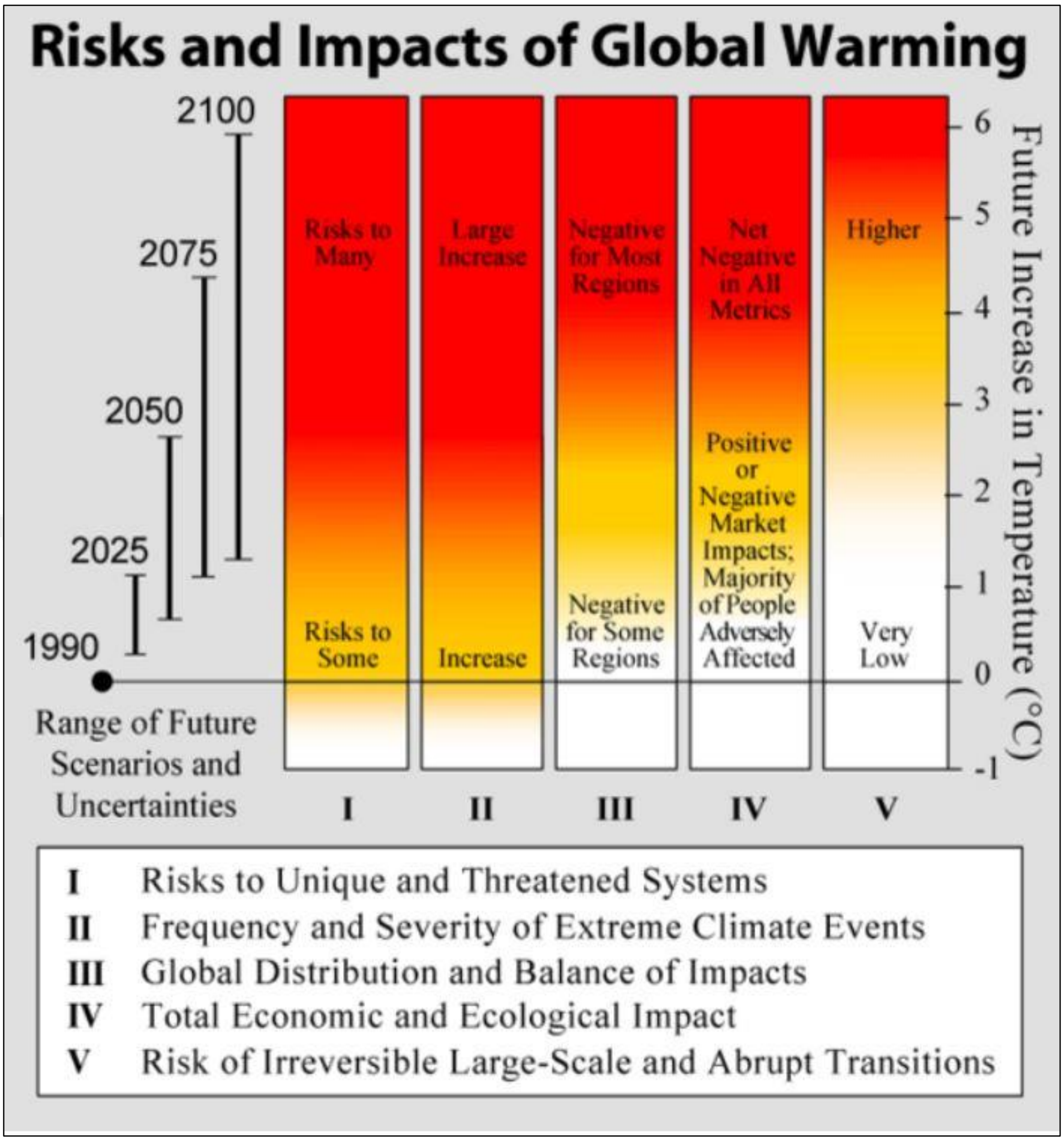

Figure 1.5. An assessment of the relative impact and risks related to global warming. The level of impact or remark for each factor is shown by the bars of color-coded when a function of temperature increase [18].

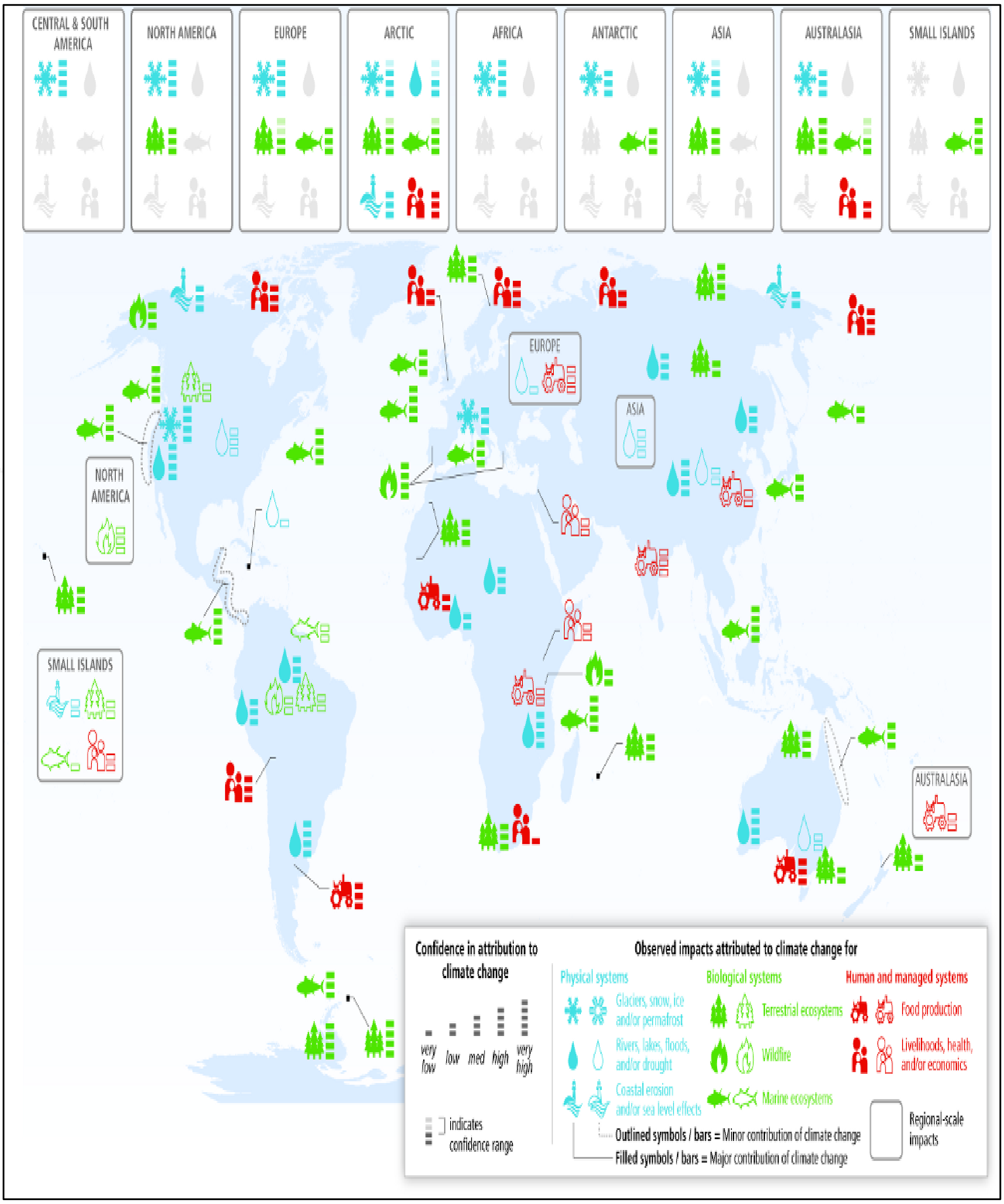

Figure 1.6. Global patterns of observed impacts of climate change. Each filled symbol in the top of panels displays a class of systems for which climate change has a key part in detected variations in at least one system within that class across the respective region, with the variety of assurance in imputation for those district-widespread effects displayed by the bars. Outlined symbols in a box in the respective region shown regional-scale impacts where climate change has an insignificant role. Symbols on the map show sub-regional impacts located in the estimated district of their existing. Color enables to

differentiate effects on biological indicated with green, human indicated with red systems, and physical indicated with blue [19].

According to data, when assessed the past hundred years, the warmest decade has occurred in the recent 10 years, though the inclination of global warming has almost halted since 1999. Figure 1.7 represent the temperature anomalies between 1975 and 2010 [20].

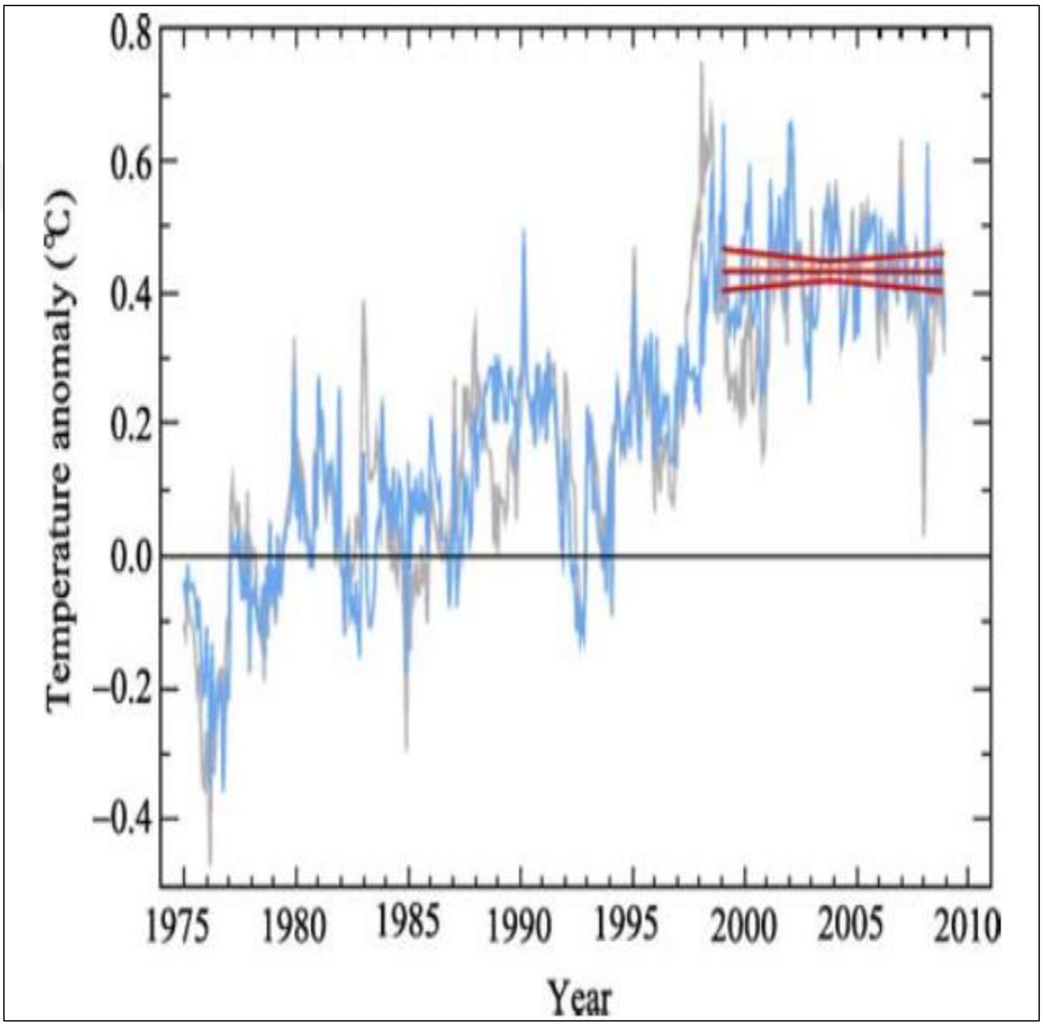

Figure 1.7. Global mean temperature abnormalities between 1961and 1990 indicated by gray, global mean temperature anomalies after removing the impact of El Niño Southern Oscillation known as ENSO indicated by blue, and temperature inclination of 1999-2008 indicated by red color [20].

In the recent 100 years, the surface temperature has become warmer by approximately 1.0°C (1.8°F) is represented by the measurements and analysis of earth's surface temperature. Figure 1.8 represents the mean annual temperature measurement of 150 years (from 1850 to 2008). Indications of atmospheric temperature made at weather situations were combined with indications of sea temperature in order that average annual temperature for the whole globe is produced. The graph displays a gradual upsurge in temperature varied between almost -0.5°C and +0.5°C which represent a minimum and maximum abnormality, respectively. In the graph, displays a stable upsurge in surface temperature between 1860 and 1910 and a prompt upsurge between 1910 and 1945, steadying for approximately 3 decades and the upsurges rapidly over after 1975. In the recent two decades, the global average temperature has been rising by 0.1°C per decade, with 2005, which was the warmest year on record. Urban heat island effect, meaning the impacts of huge population centers on the global average temperature, are calculated and modified for; on the other hand, this is responsible for less than 15 per cent of the detected global warming. Global warming is not persistent on the earth, also in time and in space; high latitude districts commonly become warmer than low latitude districts. Years of cooler temperature entrenched within the warming inclination have been experienced by wholly districts of the earth. A chaotic characteristic of climate change and global warming is indicated by the observed spatial and time-based abnormality in global warming [21].

Figure 1.8. By combination of atmospheric temperature which were gauged at whether events on mainland and sea temperature, which were gauged along ship routes on the oceans, global, mean annual temperature were obtained. This time sequences is the straight, instrumental data of global warming between 1850 and 2008 and the year 2007 was record as the year which the increase of global temperature was constant between the eight warmest year ; 2005, 2003, 2002, 2004, 2006, 2001 and 1998 [21].

Scientists predict that additional the upsurges in greenhouse gas level this century will partake a largely warming effect on the climate, for climate change after 50 or 100 years from now. However, it is hard to say how potent the impact will occur. As a result of greenhouse gas emissions, a strong warming will happen in the mid- layer of the atmosphere over the topics, and this has not been detected in data to date. If it happens, although local impacts in specific districts are too hard to forecast dependably, climate change can influence snow tends, sea levels, precipitation and, ice, storminess, and numerous other climate features [9].

It is predicted that the upsurges in global average temperature surpassing 1.5-2.5ºC and in contaminant concentration of atmospheric carbon dioxide will result in be important changes in ecosystem infrastructure and role, species' ecological interactions, and species' geographical varieties, with commonly negative results for ecosystem and biodiversity; services and goods like food supply and water [17].

1.3. HONEYBEE COLONY

Western honeybee, *Apis mellifera,* lives in a large geographical area extending through Africa, Europe and Western Asia [22]. Colony of honeybees contains a single queen, hundreds of male drones and 20,000 to 80,000 female worker bees, developing eggs, larvae and pupae. The queen is responsible for laying the eggs and producing the colony [23]. Development of the castes of the colony occurs during transition through egg, larva, pupa and adult stages. The larval stage is the feeding time, where the bee grows tremendously in size and gains weight. The unfertilized eggs transform into drones [24]. When the eggs hatch, all the female larvae are fed with royal jelly, made by the worker bees by chewing pollen and honey. The worker bees are fed with the royal jelly only for three days, the larvae, which are chosen to develop into queen are continued to be fed with the royal jelly in the forthcoming days too [25–27]. The larvae spin their cocoons and change into pupae after the adult workers cap their cells [28]. The pupal stage is a phase of metamorphosis, where transformation is completed and the brood become adults. The immature adults chew their way out of the cells and finish their development during the next few days. The whole process from egg to adult may take about 16 days for queens, 21 days for workers and 24 days for drones [29]. Workers clean the colony, regulate its temperature, forage for nectar, pollen, water and propolis, and also find new homes for a swarm when needed, develop stinging mechanisms, dance languages, convert nectar into honey and defend the hive from all improper intrusion, destroy the drones after mating, kill and remove the unnecessary queens and remove the old worker bees from the colony [30]. Propolis, also called the bee glue, is a resinous mixture collected from the trees or other plants and used to seal the unwanted open spaces in the hive. Workers typically live 3-6 weeks during the spring and the summer and may live about four months during the winter. When a virgin queen mates with a drone on a mating flight the fertilized eggs transform into females [31]. Queens normally live less than a year in the commercial hives. Estimates of average life span for drones vary from about 20 to 40 days [32]. Figure 1.9 shows the castes of the honeybee colony.

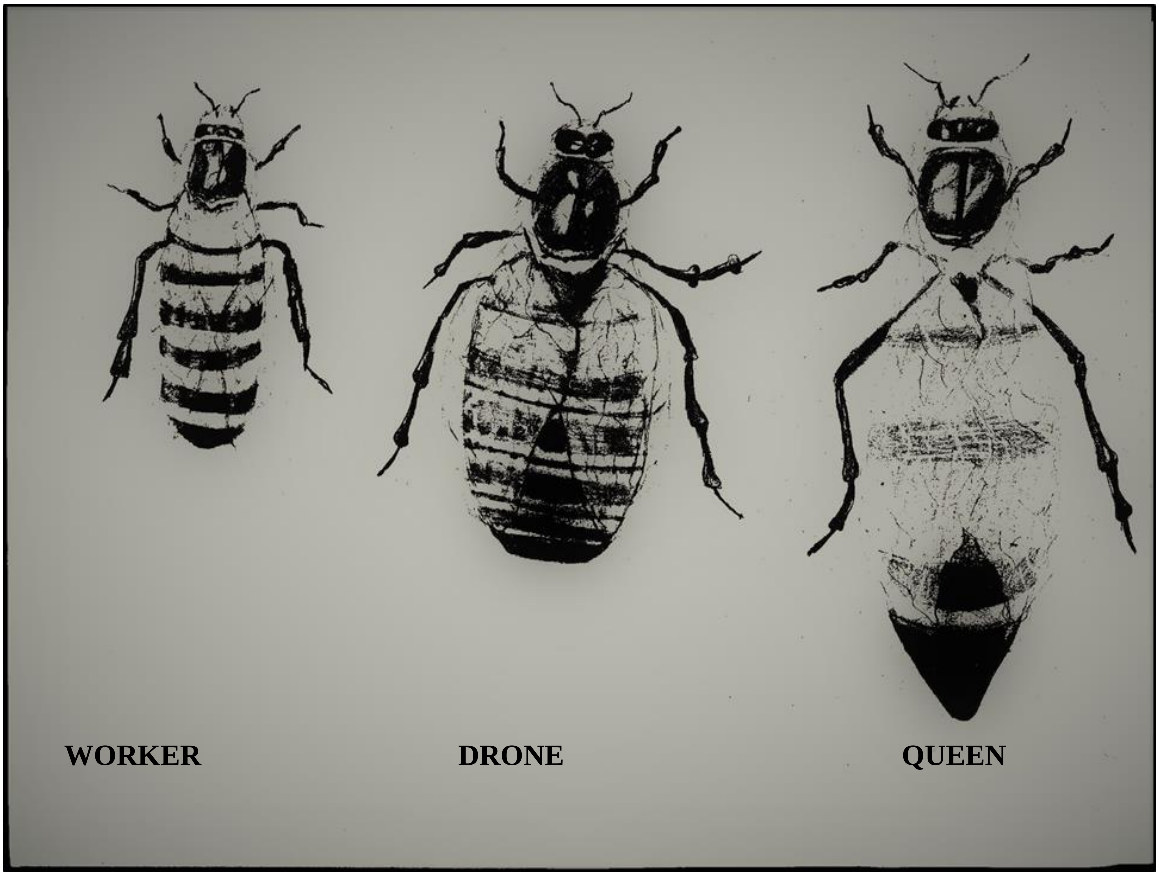

Figure 1.9. Castes of the honeybee colony, *Apis mellifera*

1.4. THE BEHAVIOR OF HONEYBEES THROUGHOUT A YEAR

The activity of the honeybees starts in the beginning of spring relying on the temperature. If the weather becomes warmer, the days lengthen, and flowers blooms, the queen lays eggs, and the honeybees start foraging for nectar and pollen from early flowers [33]. Late in spring, brood of honeybee larvae and its population size increase.

Between the spring and early summer, which encourages the fresh colony to become enormous in order to keep sufficient honey in reserve throughout summer and autumn to prepare the colony through winter conditions, honeybee colony swarm to reproduce itself, as different from reproduction of individuals within the colony. Therefore, honeybees maintain the survival of species. By swarming which is generally a properties of colonies consisting of huge numbers of worker honeybees and an active laying queen [34].

In summer, honeybee colonies must produce a population, which has enough lifespan to survive during the long winter with substantial variation in temperatures. If the colony is infected by parasites in summer, or the foraging opportunities are limited due to poor weather, the colony may be prevented from building up a population with enough lifespan to survive winter and thus increase the risk of winter loss [35].

Honeybees become stress due to temperatures over 37°C [33], and must maintain the temperature in the brood area at 35^{o}C to 36^{o}C. When it is warm, The workers fans their wings to cool the hive using collected water, but if it becomes excessively hot, they hang in a cluster outside the hive during the day and even in the evening [36].

During summer, they go on collecting pollen, nectar and water and producing honey. They store honey for the winter season.

During autumn, the population has long-lived "winter" bees, and increases fat bodies, and protein reserves when brood rearing reduces pollen consumption increases [37]. Winter bees may live much longer than summer bees because winter bees are not affected by the risk associated with foraging [32].

In autumn, honeybees regulate the termination of brood rearing, store large amount of honey for thermoregulation and sufficient protein for late winter and early spring brood-rearing [38].

During the winter, honeybees muster inside of the hive and terminate their center of the colony from which they move from time outside actions. They became the form of a tight cluster at the center of the to time to feed on stored honey [36].

During the winter, when temperature of the hive dips below 18-19^{o}C, workers cluster become organize and raise their metabolic rate to produce heat. Workers that bring into being the winter cluster in the brood area dissipated the heat from their thoracic flight muscles.

When temperature of the hive dews drop from 28°C to 17°C, the metabolic rate of a honeybee colony increases from 7 to 19 Watt/kg. The “cluster” also constricts when the temperature changes between -5 and -18°C. Due to the harsh winter circumstances of temperate climates, numerous honeybee colonies weaken or finally die. As a result, the reduction in honey production often occurs in the following active season. High honey yields can be produced by only strong honeybee colonies in temperate and subtropical conditions [39].

Some of a winter cluster’s honeybees are endothermic, and greatest of these honeybees are positioned inside the cluster even though these bees are not in prompt danger of freezing or falling into chill coma [40].

1.5. LIFE OF A WORKER HONEYBEE

Most of the life of a worker honeybee is devoted to foraging for resources outside the hive. The foragers collect especially nectar and pollen to supply food for the colony, minority of the foragers also collect water and propolis [41,42]. When a forager finds a new pollen resource, she communicates with the other workers in the nest through waggle dance to describe the exact location of food source [43–45]. The bees perform the waggle dance by making an angle to fly with respect to the sun [46]. After a successful forage, some of the worker bees perform the waggle dance again for new recruits [47]. Returning foragers carry pollen to the colony on the outside of their body, packed onto special structures, corbiculae, of their hind legs and deposit their loads directly into wax cells situated around the brood rearing areas of the nest [48]. Nurse bees help incubating the brood and preparing the brood cells, and then they feed the raising larvae with bee bread and the older larvae with a mixture of honey and pollen [49]. Beebread is made of pollen mixed with digestive enzymes and preserved with honey and bee wax.

When the foraging honeybees visit flowers to collect pollen, they transport it from a pollinator to a flower and enable their reproduction [50]. Pollination of flowers is a crucial step in the sexual reproduction of angiosperms [51]. When foraging, *A. mellifera* may show floral constancy represented by repeated visits from a pollinator to flowers [52]. Insect pollination is necessary for 75 per cent of the crops used directly by the people worldwide, including sunflower, grapes, almond, olive, spices, apple, apricot, avocado, water melon, kiwifruit, peach, cotton, orange, eggplant, chestnut and many others [53]. Pollination is among the most important ecosystem processes facilitating plant fertilization [54]. Although honeybee is the most effective pollinator in the open field, it is not a suitable pollinator for winter-fruit production in the greenhouses, since it is affected by irregular heating, insufficient pollen production, low temperature and low light intensity [55]. However, modern studies show that synchronization of pollinator activity and flowering may be affected by climate change [56].

1.6. THE RATE OF METABOLISM AND HEAT AND MASS EXCHANGE OF A THERMOREGULATING HONEYBEE

An organism is called *ectothermic*, if it lacks an internal mechanism for regulating body heat, therefore its body temperature would be close to that of the environment. An *endothermic* organism, on the other hand, maintains a certain body temperature regardless of the environmental temperature. The honeybees behave like ectothermic insect when resting and like an endothermic organism while foraging [57]. While foraging at low environmental temperatures, they make massive effort to maintain their body temperature and metabolize larger amounts of sucrose. However, as temperature increases demand for sucrose decreases and they metabolize smaller amounts of sucrose. Therefore, the rate of the metabolism of a flying honeybee decreases significantly with rising ambient temperature [58,59]. The large surface to volume ratio of the body of the honeybee is among the factors which make the energy demand so high at low temperatures, since the environmental factors, such as the ambient air temperature, solar radiation and convection[60,61] promote higher heat and mass transfer rates in such geometry.

Convective heat changes depend on the temperature difference between the ambient environment and the body; forced convection depends also on the speed of the air [62]. The foraging honeybees may thermoregulate actively by decreasing their mechanical power output at high ambient temperatures by changing the kinematic flight variables such as the wingbeat frequency and stroke amplitude. Honeybees flying at high ambient temperatures may increase the efficiency of conservation of metabolic and mechanical power by changing their flight behaviors that could potentially affect their work performance and the subsequent metabolic rate [59]. During foraging at elevated air temperatures, water produced by the metabolic activity is evaporated, since it removes heat from the honeybees and prevents overheating [62]. The rate of evaporation of water depends on the consumption rate of the O_2 and the production rate of the CO_2.

Honeybees maintain high and stable colony temperatures in the hives by coordinated thermoregulation. Ventilation of the hive by fanning is a social thermoregulatory measure and also means of accelerating the nectar concentration process [63]. Individual foragers maintain high flight muscle temperatures by active endothermy. Muscular performance of the honeybees is impaired below about 28°C of thoracic temperature. Below 12ºC of thoracic temperature chill coma or generalized muscular paralysis develops [64].

1.7. EFFECT OF THE CLIMATE CHANGE ON THE HONEYBEES

To indicate climate change, insects are more useable organisms because of their biological features: they are little and poikilothermic, thus their thermoregulation and following motion are strongly influenced by the changeability of the climate [65]. Organisms (such as a frog) with a variable body temperature that tends to fluctuate with, or slightly higher, than the temperature of its environment are called poikilothermic or cold-blooded. Climate change is a global phenomenon which affects every component of the agricultural ecosystem, it influences the bees and their pollination efficiency at various ways [66]. Anomalous seasons and climatically variable years on the habitat of the bees change the plant-pollinator interactions [67]. The population size of the honeybees is affected by the changes in the temperature, precipitation and the other whether events. Their survival and reproduction are also affected indirectly via the negative effects on the resource availability and interspecies interactions [68]. The level of harmony between the genotype and the environment affects the productivity of the genotypes under the regional conditions [69]. Broods of honeybee larvae depend on warm temperature to survive and an early spring cold can kill developing workers resulting in loss the pollinators for the flowers [70]. If the climate condition becomes unsuitable for the honeybees, they may move to another more suitable area for their survival and reproduction. As a result, the plants lose their pollinators [71]. The climate change may potentially interfere with the plant - pollinator interactions, destabilize the ecosystems and present severe consequences for the human food security, especially after considering that more than pollination is necessary for 75 per cent of the crops used directly by the people worldwide [53][72]. Ecological cycle is defined as the continuing movement of carbon, nitrogen, oxygen, water and similar substances, which are important for living, in a self-regulating mechanism between the earth's crust, the atmosphere and the oceans. Acceleration or degradation of ecological cycles by human activities can sometimes lead to irreversible problems in the ecosystem [73]. Therefore, the variety and growth of plants are affected and decrease of the flowering plant leads to the decline of the honeybee populations. Global warming increases the temperature of the environment, T_a, where the honeybees live in. As the average monthly temperature rises, flowers bloom earlier in the spring and cause honeybees to lose their food resource because of the mismatch in seasonal timing [74,75]. When food availability enhances, the number of ovarioles comprising the ovaries increases. However, larval food limitation reduces the number of the worker ovarioles [76].

In the present study, honeybees are chosen as an indicator pollinator organism because the climate change affects the interrelation between the honeybee, its plant environment and diseases [77]. Since the honeybees contribute to the pollination of numerous agricultural crops worldwide [78] the climate change will affect the bees first, but then trigger massive changes including endangering the food safety of the people. Ambient temperature and moisture, availability and energy of the nutrients and the nutrient energy will affect the heat and mass exchange rates of the bees with the environment and the laws of the thermodynamics, which govern the sustainability of their lives. In the present study, impact of the environmental changes on the thermodynamic properties of the honeybees will be assessed.

2. MATERIALS AND METHOD

2.1. PHYSICAL PROPERTIES OF THE HONEYBEES

Average weights of a freshly emerged worker and adult honeybees were 116 [79] and 84 mg [80], respectively. The volume and surface area of the thorax were expressed as [81]:

$$V_{thorax} = \frac{4}{3}\pi R_{tho}{}^{3} \tag{2.1}$$

$$S_{thorax} = 4\pi R_{tho}{}^{2} \tag{2.2}$$

$$2R_{thorax} = 2.3\ mm \tag{2.3}$$

$$D_{bodypart} = [(6/\pi)\ V_{bodypart}]^{1/3} \tag{2.4}$$

where R_{tho} is the radius of the spherically shaped thorax, D is the characteristic dimension of the body part of interest.

2.2. CALCULATIONS REGARDING METABOLIC ACTIVITY

Sucrose was the major energy source of the honeybees. It was first hydrolysed into glucose and fructose as described in (2.5), and then fructose and glucose are metabolized as described in (2.6).

$$C_{12}H_{22}O_{11(aq)} + H_2O_{(l)} \longrightarrow C_6H_{12}O_{6(aq)} + C_6H_{12}O_{6(aq)} \tag{2.5}$$

$$C_6H_{12}O_{6(s)} + 6O_{2(g)} \longrightarrow 6CO_{2(g)} + 6H_2O_{(l)} \tag{2.6}$$

Equation (2.6) summarizes the energy metabolism, all the calculations of this study are based on this equation. Experimental data of CO_2 production rates of the foraging honeybees provided by Stabentheiner *et. al.*,(2016) [82] and experimental data of O_2 consumption rates of the resting honeybees presented by Stabentheiner *et al.*, (2003) [57] were used to calculate their rates of metabolism, glucose and sucrose utilization and water generation by referring to (2.6).

Carbon dioxide and oxygen were assumed ideal gases while carrying out the calculations presented in Tables 2.1 and 2.2. Energy and entropy generation by the honeybees were discussed based on (2.6). As expressed by the Hess's law (Mahan 1969) [83], energy is a state function, energy difference between two states does not depend on the pathway followed. The original method used to determine the nutritional calories of foods or their constituents like sucrose or glucose was measuring directly the energy it produced by burning it completely in a bomb calorimeter. In the bomb calorimeter, combustion chamber is surrounded by water and the resulting rise in water temperature is measured (FAO 2002) [84]. When the food burned in the bomb calorimeter and utilized in the metabolism produces the same chemical reactants this method produces reliable results as suggested by the Hess's law. Feinman and Fine (2004) [85] after comparing the combustion of glucose and its utilization in the metabolism state that in the combustion process 60 per cent of the chemical energy of glucose is wasted with heat, whereas in metabolism it is retained in the cell in the form of ATP. Mady and de Oliveira (2013) [86] rephrased this observation, as "*the fraction of the exergy of the nutrients retained within the bounds of the ATP in the body was about 60 per cent".*

Enthalpy change in the reaction described by (2.6) under the standard conditions ($T=25^oC$, $P=1$ atm) is

$$\Delta h_{rxn}{}^{\circ} = \{6\Delta fh^{\circ}{}_{CO_2} + 6\Delta fh^{\circ}{}_{H_2O}\} - \{\Delta fh^{\circ}C_{6H_{12}O_6} + 6\Delta fh^{\circ}{}_{O_2}\} \tag{2.7}$$

where, $\Delta fh^{\circ}{}_{CO_2}$ and $\Delta fh^{\circ}{}_{H2O}$ represent the enthalpy of formation of products and $\Delta fh^{\circ}C_{6H12O6}$ and $\Delta fh^{\circ}{}_{O2}$ represent the enthalpy of formation of reactants under the standard conditions. Thermodynamic properties of the chemicals are presented in Table 2.3.

At temperatures other than those of the standard conditions, enthalpy of formation of the chemicals were calculated as:

$$\Delta h_T = \Delta h°_{298} + \int_{298}^{T} c_p dT \qquad (2.8)$$

Molar heat capacity over the temperature range of 298 to 308 K was [87]:

$$c_p\ (J/mol\ K) = 5.410 + 0.7173T \qquad (2.9)$$

In the studies regarding water exchange and water balance of animals, it is often necessary to estimate the metabolic water. Where water intake is usually measured, specifically it is important to consider this metabolic component along food moisture, as these can greatly modify the interpretation to be placed on variations in purely fluid intake [88]. Metabolic water formation is calculated with (2.10):

$$\begin{gathered} \textit{Metabolic water formed } (g) = 0.1998 \text{ x } \textit{liters } O_2 \textit{ consumed} + \\ 0.4692 \text{ x } \textit{liters } CO_2 \textit{ produced} \end{gathered} \qquad (2.10)$$

Table 2.1. Rates of oxygen and water uptake, carbon dioxide and metabolic water production

T_a (K)	**Rate of oxygen up take (g/min)**	**Rate of water up take (g/min)**	**Rate of CO_2 production (g/min)**	**Volume of O_2 consumption (µl/min)**	**Rate of metabolic water output (g/min)**
1-7 h old young honeybees resting in the hive at atmospheric pressure with 0.5 M of sucrose supply with 15 µl/min flow					
288	1.3×10^{-6}	6.3×10^{-7}	1.7×10^{-6}	0.94	7.1×10^{-7}
298	1.5×10^{-6}	7.5×10^{-7}	2.0×10^{-6}	1.12	8.3×10^{-7}
308	3.7×10^{-6}	1.9×10^{-6}	5.1×10^{-6}	2.90	2.1×10^{-6}
T_a (K)	**Rate of oxygen up take (g/min)**	**Rate of water up take (g/min)**	**Rate of CO_2 production (g/min)**	**Volume of CO_2 consumption (µl/min)**	**Rate of metabolic water output (g/min)**
Foraging honeybees under the sun shine at atmospheric pressure with 0.5 M of sucrose supply with 15 µl/min flow rate					
288	1.7×10^{-4}	8.6×10^{-5}	2.4×10^{-4}	128.3	9.8×10^{-5}
298	5.8×10^{-5}	2.98×10^{-5}	8.0×10^{-5}	44.6	3.3×10^{-5}
308	1.5×10^{-5}	7.99×10^{-6}	2.1×10^{-5}	12.0	8.5×10^{-6}
Foraging honeybees, at shade, under the atmospheric pressure with 0.5 M of sucrose supply with 15 µl/min flow rate					
288	2.2×10^{-4}	1.10×10^{-4}	3.1×10^{-4}	165.2	1.3×10^{-4}
298	1.2×10^{-4}	6.6×10^{-5}	1.7×10^{-4}	98.5	6.9×10^{-5}
Foraging honeybees, under the sun shine at atmospheric pressure with 0.5 M of unlimited sucrose supply					
288	2.4×10^{-4}	1.21×10^{-4}	3.4×10^{-4}	180.5	1.4×10^{-4}
298	2.1×10^{-4}	1.08×10^{-4}	2.2×10^{-4}	162.0	1.2×10^{-4}
308	7.6×10^{-5}	3.99×10^{-5}	1.4×10^{-4}	59.8	4.3×10^{-5}
Foraging honeybees, at shade under the atmospheric pressure with 0.5 M of unlimited sucrose supply					
288	2.2×10^{-4}	1.10×10^{-4}	3.1×10^{-4}	165.2	1.25×10^{-4}
298	2.3×10^{-4}	1.18×10^{-4}	3.2×10^{-4}	176.1	1.3×10^{-4}
308	1.1×10^{-4}	5.8×10^{-5}	1.5×10^{-4}	87.0	6.2×10^{-5}

Table 2.2 Amounts of sucrose hydrolyzed and glucose plus fructose consumed by the foraging honeybees under the sunshine and shade at 15°C, 25°C and 35°C.

	$C_{12}H_{22}O_{11}$		$C_6H_{12}O_6$	
1-7 h old young honeybees resting in the hive at atmospheric pressure with 0.5 M of sucrose supply with 15 µl/min flow				
T_a (K)	**(mol/min)**	**(g/min)**	**(mol/min)**	**(g/min)**
288	6.6 x10^{-9}	2.3 x10^{-6}	6.6 x10^{-9}	1.2 x10^{-6}
298	7.6 x10^{-9}	2.6 x10^{-6}	7.6 x10^{-9}	1.4 x10^{-6}
308	1.9 x10^{-8}	6.6 x10^{-6}	1.9 x10^{-8}	3.5 x10^{-6}
Foraging honeybees, under the sun shine at atmospheric pressure with 0.5 M of sucrose supply with 15 µl/min flow				
288	9.05 x10^{-7}	3.1 x10^{-4}	9.05 x10^{-7}	1.6 x10^{-4}
298	3.038 x10^{-7}	1.04 x10^{-4}	3.038 x10^{-7}	5.5 x10^{-5}
308	7.89 x10^{-8}	2.7 x10^{-5}	7.89 x10^{-8}	1.4 x10^{-5}
Foraging honeybees, at shade, under the atmospheric pressure with 0.5 M of sucrose supply with 15 µl/min flow rate				
288	1.165 x10^{-6}	3.9 x10^{-4}	1.165 x10^{-6}	2.1 x10^{-4}
298	6.375 x10^{-7}	2.2 x10^{-4}	6.375 x10^{-7}	1.2 x10^{-4}
Foraging honeybees, under the sun shine at atmospheric pressure with 0.5 M of unlimited sucrose supply				
288	1.273 x10^{-6}	4.4 x10^{-4}	1.273 x10^{-6}	2.3 x10^{-4}
298	1.104 x10^{-6}	3.8 x10^{-4}	1.104 x10^{-6}	1.9 x10^{-4}
308	3.945 x10^{-7}	1.4 x10^{-4}	3.945 x10^{-7}	7.1 x10^{-5}
Foraging honeybees, at shade under the atmospheric pressure with 0.5 M of unlimited sucrose supply				
288	1.166 x10^{-6}	3.9 x10^{-4}	1.166 x10^{-6}	2.1 x10^{-4}
298	1.201 x10^{-6}	4.1 x10^{-4}	1.201 x10^{-6}	2.2 x10^{-4}
308	5.738 x10^{-7}	1.9 x10^{-4}	5.738 x10^{-7}	1.0 x10^{-4}

Table 2.3. Thermodynamic properties of the chemical

Thermodynamic properties of the chemicals, enthalpies of glucose, O_2 ,CO_2, and H_2O at 1 atm (adapted from Kuddusi, 2015)[89]			
chemical	$\bar{h}_f^{\circ}$ **(kJ/kmol)**	$\bar{h}_{298K}$ **(kJ/kmol)**	$\bar{h}^{\circ}_{310K}$ **(kJ/kmol)**
$C_6H_{12}O_6$	-1260 x 10^3	-	-
O_2	0	-	-
H_2O	-241820	9904	10302
CO_2,	-393520	9364	9807
Thermodynamic properties of the chemicals, enthalpies of CO_2, H_2O and O_2 at 1 atm [90]			
Ta (K)	h_{CO2}**(kJ/kmol)**	h_{H2O}**(kJ/kmol)**	h_{O2}**(kJ/kmol)**
288	9044	9564	8384
298	9364	9904	8682
308	9732	10235	8971
Enthalpy of formation of glucose, CO_2 and H_2O at 1 atm, 298 K (data has been adapted from Kabo (2013) [87]).			
chemical	**-** $\Delta_f h^{\circ}_{rxn}$ **(kJ/mol)**		
$C_6H_{12}O_6$	1273.94		
CO_2	393.51		
H_2O	285.83		
Enthalpy change of the sucrose hydrolysis reaction at 1 atm; data has been adapted from Goldberg (1989) [91].			
T_a(K)	**-** Δh_{rxn} **(kJ/mol)**		
288	-		
298	14.946		
308	14.372		
Entropies of glucose, O_2, CO_2 and H_2O at 1 atm (adapted from Kuddusi, 2015 [70].			
chemical	s_i^{-}		
$C_6H_{12}O_6$ (298K)	212		
O_2 (298K)	218.02		
H_2O(310K)	240.4		
CO_2(310K)	215.5		

According to Stabentheiner and Kovac (2014) [92], the total amount of sucrose by the foraging honeybees with supply 1.5 M of unlimited sucrose flow in 6 hours was calculated. The amount (mg) imbibed in the shade and under the sunshine were

$$65.7741 - 0.03975 \text{ x } T_a \text{ and } 45.70473 + 0.85964 \text{ x } T_a\text{, respectively}$$

The amount (mg) imbibed in the shade and under the sunshine were

$$65.7741 - 0.03975 \text{ x } T_a \text{ and } 45.70473 + 0.85964 \text{ x } T_a\text{, respectively.}$$

2.3. CALCULATION OF THE HEAT TRANSFER TO AND FROM THE FORAGING HONEYBEES

Heat exchange and the solar radiation exposure rates for the foraging honeybees were calculated by performing mass and energy balances around the systems described in Figures A1a and 1b. Parameter h_{thorax} is the coefficient of the forced convection heat transfer from thorax evaluated from (2.11):

$$hD/k = 2 + (0.4Re_D^{1/2} + 0.06Re_D^{2/3})\, Pr^{0,4}(\mu/\mu_s)^{1/4} \tag{2.11}$$

This correlation is valid in the Reynolds number ($Re_D = D\rho U/\mu$) range of 3.5 to 7.6×10^4 and in the Prandtl number range of 0.71 to 380. The changing of Reynolds number with air velocity at different temperatures is shown in Table 2.5. In (2.11) and (2.12), D is the diameter of the thorax and k, c_p, ρ, and μ are the thermal conductivity, specific heat, density and dynamic viscosity of the air evaluated at the temperature of the surroundings as presented in Table 2.4. The temperature-dependence correction factor of viscosity μ/μ_s was 1. Parameter U is the speed of the air past the bee. The relation between convection and conduction heat transfer coefficients during natural convection was:

$$hD/k = 2 + 0.589R_{AD}^{1/4}[1 + (0.469/Pr)^{9/16}]^{4/9} \quad (2.12)$$

where R_{AD} refers to the Rayleigh number $[R_{AD} \equiv g|T_{tho} - T_{surr}|D^3/(\nu\alpha T_{surr})]$ and Pr refers to the Prandtl number ($Pr=\mu c_p/k$). This correlation is valid when $R_{AD} \leq 10^{11}$ and $Pr \geq 0.7$. Values of the thorax temperature T_{th} depends on ambient temperature and adapted from Stabentheiner and Kovac (2016) [82]. Rayleigh number and h_{thorax} at different conditions are presented in Table 2.6.

Heat exchange rate of the honeybees with the environment is expressed as:

$$Q = hA[T_{tho} - T_{surr}] \quad (2.13)$$

Incoming long wave radiation (L↓) to the honeybees was estimated as (Swinbank, 1963):

$$L= \delta T_a^6 \quad (2.14)$$

where, $\delta=5.31 \times 10^{-13}\ Wm^{-2}K^{-6}$ and T_a is the air temperature.

Outgoing long wave radiation (L↑) was estimated by using the Stefan-Boltzman relation:

$$L= \sigma Ts^4 \quad (2.15)$$

where T_s the ground surface temperature, $\sigma = 5.67 \times 10^{-8}\ Wm^{-2}K^{-4}$

and T_s is the honeybee surface temperature, which is assumed to be the same as the temperature of the air for a flying honeybee [93].

Table 2.4. Physical properties of air at 1atm

T_a (°C)	μ (kg/m.s)	ρ (kg/m³)	ν (m²/s)	c_p (J/kg.K)	k (W/m.K)	Pr	α (m²/s)
15	1.802×10^{-5}	1.225	1.47×10^{-5}	1007	0.02476	0.7323	2.009×10^{-5}
25	1.849×10^{-5}	1.184	1.562×10^{-5}	1007	0.02551	0.7296	2.141×10^{-5}
85	1.895×10^{-5}	1.145	1.655×10^{-5}	1007	0.02625	0.7268	2.277×10^{-5}

* Prandtl, Reynolds and Rayleigh numbers are calculated with the physical property data adapted from Çengel [94].

Table 2.5. Variation of h_{th} with air velocity and Reynold numbers

U=0.5 m/s		
T_a (K)	**Re**	**h_{th}**
288	78.2	65.6
298	73.6	66.1
308	69.5	66.5
U=1.0 m/s		
T_a (K)	**Re**	**h_{th}**
288	156.4	85.6
298	147.3	86.0
308	139.0	86.4

Table 2.6. The values of T_{th}, h_{th} and R_{AD} under the sunshine and at shade at 15, 25 and 35°C

T_a (°C)	**R_{AD}**	**h_{th}**	**T_h (°C)**
Under the sun shine at atmospheric pressure with 0.5 M of sucrose supply with 15 µl/min flow rate			
15	33.8	41.3	39.1
25	15.2	38.9	37.7
35	4.0	35.1	38.9
At shade, under the atmospheric pressure with 0.5 M of sucrose supply with 15 µl/min flow rate			
15	30.7	40.8	36.9
25	14.7	38.7	37.3
35	-	-	-
Under the sun shine at atmospheric pressure with 0.5 M of unlimited sucrose supply			
15	36.7	41.7	41.1
25	19.0	39.8	40.8
35	5.1	35.9	40.0
At shade under the atmospheric pressure with 0.5 M of unlimited sucrose supply			
15	31.4	40.9	37.4
25	17.3	39.4	39.5
35	4.0	35.2	38.7

2.4. FIRST LAW OF THERMODYNAMICS AS APPLIED TO THE HONEYBEES

After assuming that the honeybees were under steady state, the first law of thermodynamics was applied to the adult honeybees and 1-7 h old young resting as described in (2.16) and (2.17), respectively:

$$\sum [\dot{m}_{in}h_{in}] - [\dot{m}_{out}h_{out}] \pm Q - W + \delta T_a^6 + \sigma T_s^4 = \frac{d[m(u)]}{dt} \tag{2.16}$$

$$\sum [\dot{m}_{in}h_{in}] - [\dot{m}_{out}h_{out}] - W = \frac{d[m(u)]}{dt} \tag{2.17}$$

the boundaries of this system are described in Figure A.1a and 1b. Thermodynamic properties h_{in} and h_{out} are presented in Table 2.3; Q shows the heat received by the bees, $\delta T_a^6$and σT_s^4 represent the radiation heat uptake. Variables m_{in} referring to oxygen, water, sucrose, and m_{out} referring to carbon dioxide and evaporative water are presented in Tables 2.1 and 2.2. Oxygen consumption rates by 1-7 h old young resting honeybees (which were free to move) were obtained at 15, 25 and 35^{o}C in Warburg vessel as described by Stabentheiner *et al* (2003) were presented in Table 2.1.

2.5. VENTILATION OF AIR

The rate of oxygen consumption presented in Table 2.7 was calculated based on the data presented by Southwick (1987)[95] and then then rates of metabolism during ventilation of air were calculated like the calculations of metabolic rate of foraging and resting honeybees by using (2.5), (2.6) and (2.7). The metabolic energy utilized while raising or reducing the temperature of the hive by 1^{o}C by honeybee was estimated. Psychrometric chart was used in the calculation of the heat and work generation during cooling and heating of the hive by 3,000 honeybees, where $W = -\frac{(\Delta H)}{\gamma}$ [96] and $\gamma = \frac{cp}{cv} = 1.4$ [97].

Table 2.7. Rates of oxygen uptake, sucrose hydrolysis during ventilation of air

T_a (K)	Rate of oxygen uptake (mol/min)	Volume of oxygen consumption (ml/min)	Rate of sucrose hydrolysis (mol/min)
296.89	7.76×10^{-3}	18.96	1.29×10^{-3}
297.36	7.82×10^{-3}	19.12	1.30×10^{-3}
297.78	7.77×10^{-3}	18.95	1.295×10^{-3}
298.14	7.53×10^{-3}	18.34	1.26×10^{-3}

2.6. ENTROPY GENERATION RATE

Organisms eat up high-energy nutrients irreversibly to continue the duration of life, therefore generate heat and entropy, yet entropy is also transposed into the environment through numerous waste streams covering heat transfer via the skin and perspiration, in order that the biological system is maintained at fixed thermal state [98]. Entropy balance during resting, foraging and fanning around the systems described in Figure A1 may be represented with (2.18) at 1 atm [99].

$$(\sum NS)_{out} - (\sum NS)_{in} - \sum \frac{Q}{T} = \Delta S_{gen} \qquad (2.18)$$

In this equation, N represents mol number of chemicals entering or leaving the system, S is the entropy per unit mole of i^{th} component (i gas in the mixture) (Table 2.3). T is the temperature of the environment, which means outdoor temperature for foraging honeybees and temperature of the hive for resting and fanning honeybees, and Q is the heat exchange with the environment, which is responsible for entropy generation (2.21).

To calculate the heat which is responsible for entropy generation via metabolization of glucose via (2.6), the same procedure was employed as Kuddusi (2015)[89]. For mol number of chemicals entering and leaving the system, Tables 2.1, 2.2 and 2.7 (for the mol number of carbon dioxide, water and glucose, the oxygen consumption rate, Table 2.7 was used) were used. Heat transferred from the body of the honeybee also transfers entropy at the same time, resulting in entropy generation. In the present study temperatures of the skin and environment were assumed to be $T_{skin} = 37^{o}C$ and $T_{env} = 25^{o}C$, respectively. T_{env} represents the temperature of the foods consumed and T_{skin} represent the temperature of reaction.

$$Q = \sum n_p\left(h_f^{-\circ} + h^{-} - h^{-\circ}\right)_p - \sum n_r\left(h_f^{-\circ} + h^{-} - h^{-\circ}\right)_r \qquad (2.19)$$

where, n_p and n_r show the mole number of products and reactants, $h_f^{-\circ}$, $h^{-}$and $h^{-\circ}$ are the formation enthalpies at the standard conditions (Table 2.3), respectively. Like the heat engines, a honeybee performs work with the heat generated by its body. Metabolic efficiency of a honeybee is defined as the ratio of total work obtained from the ATP molecules it produced in its metabolism and the total heat it generated:

$$\eta = \frac{W_{ATP}}{Q} = \frac{Total\ work\ obtained\ from\ ATP\ molecules}{Total\ heat\ production(Eq.19)} \qquad (2.20)$$

$where\ \eta = 0.34$. Heat allocated to entropy generation was

$$Q_{entropy} = Q\ (1 - \eta) \qquad (2.21)$$

Feinman and Fine (2004) [85] and Mady and de Oliveira (2013) suggested that 60 per cent of the energy extracted from the metabolization of glucose was embedded into the ATP molecules in the energy metabolism. ATP produced in the energy metabolism is employed for either work performance or heat generation, here η was 0.34 as suggested by Kuddusi (2015) [89] . When η = 0.34, (Eq.20) suggests that for every unit of work performance by the honeybees, approximately three units of heat is generated. This suggestion is also consistent with the argument put forward by Hall and Guyton (2016) [100]. When we consider that the honeybees heat the hive by beating their wings, generating three times heat of the muscle work seems quite reasonable from the biological point of view.

3. RESULTS AND DISCUSSION

3.1. RATE OF THE METABOLISM

The foraging honeybees transform the energy of the food into metabolic heat. Metabolic heat produced by the foraging honeybees under the sunshine with 15 μL/min of 0.5 M of sucrose supply at 35 °C was the minimum, e.g., 2.0 x10^{-3} W/g honeybee; and under the same conditions at 15 °C the maximum, e.g., 0.032 W/g honeybee (Table 3.1). At shade, at 35°C with 0.5 M of sucrose supply with 15 μl/min flow rate, the foraging honeybees neither performed any activity, including carbon dioxide production nor made an attempt to change the T_{th}. The foraging honeybees consume sucrose to keep their T_{th} higher than T_a; therefore, need more sucrose at low (Tables 2.2 and 3.1). The foraging honeybees metabolized 0.27 and 0.067 per cent of sucrose collected under the sunshine at 15°C as the maximum amount, and 35°C as the minimum amount, respectively. Apart from the amount of sucrose up take, metabolic energy production depends on sucrose flow rate. The increase of sucrose flow rate causes the increase in metabolic rate. The maximum metabolic heat production increased with unlimited sucrose flow rate. On the other hand, at shade, the foraging honeybees produced more metabolic heat compared to that under sunshine, since they could not benefit from the heat harvested from the solar radiation (Table 3.5). Besides, the increase in the rates of oxygen consumption parallels with the increase in the rate of metabolism (Table 2.1).

Honeybees produced 75.74 mg of honey as the maximum amount under sunshine at 35°C. However, the minimum amount of honey, 58.4 mg, was obtained under the sunshine and at 15°C (Table 3.2). The group of 3,000 honeybees performed 10,022 kJ/kg day of work under sunshine with 1.0 m/s of air velocity and – 3,224 kJ/kg day of work under the sunshine with 0.0 m/s of air velocity (Table 3.3). However, they generated 116.5 kJ/day K of entropy under sunshine and 132.2 kJ/day K of entropy at shade (Table 3.8). The increasing in the air velocity led to increase the work performed by honeybee. On the other hand, to be under sunshine is more suitable for honeybee, when we compare the amount of entropy generation rate.

The resting metabolic rate of honeybees is the baseline of the metabolic heat output, and it is important for the comparison with the exercising bees, which have active metabolic rate. (Kovac et al., 2007). In the present study, the maximum metabolic heat produced by the 1-7 h old young resting honeybees was 7.30 x10^{-5} W/g honeybee at 35^{o}C, and the minimum metabolic heat generation was 3.76 x10^{-5} W/g honeybee at 15^{o}C depending on the amount of sucrose up take (Tables 2.2 and 3.1). The maximum amount of sucrose metabolized by the honeybees was 6.6 x10^{-6} g/min at 35^{o}C, and the minimum was 2.3 x10^{-6} g/min at 15^{o}C (Table 2.2). During resting, T_{th} did not change with temperature and any part of the body of the honeybee did not move. The rate of metabolism of the 1-7 h old young resting honeybees increased with temperature. At high T_a, the rate of oxygen consumption and the carbon dioxide production increased during resting. A 1-7 h old young resting honeybee uses metabolic energy to maintain vital functions of its body.

The foraging honeybee is highly active and the rate of its metabolic heat was higher than that of the 1-7 h old young resting honeybees. The foraging honeybees need more sucrose to ensure flying energy and to keep T_{th} higher than T_a. The rate of metabolism of a foraging honeybee decreased with T_a unlike the rate of metabolic heat of the 1-7 h old young resting honeybees, since the foraging honeybee also used the energy provided by the sunshine to supply the energy required at a high T_{th}. On the other hand, the 1-7 h young resting honeybees were ectothermic during resting and did not need to change their T_{th} like the foraging honeybees.

Table 3.1. Enthalpy of glucose utilization and the total rate of heat generation in the metabolism after hydrolysis of sucrose

T_a (K)	$-\Delta_c h^o_{rxn}$ (kJ/min)	Total rate of metabolic heat production (kJ/min)	Rate of metabolic heat production (W/g honeybee)
1-7 h old young honeybees resting in the hive at atmospheric pressure, with 0.5 M of sucrose supply at 15 µl/min flow rate			
288	1.9×10^{-5}	1.9×10^{-5}	3.76×10^{-5}
298	2.1×10^{-5}	2.2×10^{-5}	5.07×10^{-5}
308	5.4×10^{-5}	5.4×10^{-5}	7.30×10^{-5}
Foraging honeybees, under the sun shine, under the atmospheric pressure with 0.5 M of sucrose supply with 15 µl/min flow rate			
288	2.54×10^{-3}	2.54×10^{-3}	0.023
298	8.51×10^{-4}	8.56×10^{-4}	7.7×10^{-3}
308	2.21×10^{-4}	2.22×10^{-4}	2.0×10^{-3}
Foraging honeybees, at shade, under the atmospheric pressure with 0.5 M of sucrose supply with 15 µl/min flow rate			
288	3.27×10^{-3}	3.27×10^{-3}	0.03
298	1.79×10^{-3}	1.80×10^{-3}	0.016
Foraging honeybees under the sun shine, under the atmospheric pressure with 0.5 M of unlimited sucrose supply			
288	3.57×10^{-3}	3.57×10^{-3}	0.032
298	3.09×10^{-3}	3.11×10^{-3}	0.028
308	1.10×10^{-3}	1.11×10^{-3}	0.010
Foraging honeybees, at shade, under the atmospheric pressure with 0.5 M of unlimited sucrose supply			
288	3.27×10^{-3}	3.27×10^{-3}	0.029
298	3.37×10^{-3}	3.38×10^{-3}	0.031
308	1.61×10^{-3}	1.61×10^{-3}	0.013

Table 3.2. The amount of honey produced by honeybee with 0.5 M of unlimited sucrose flow

Under sunshine P=1atm	
T_a (K)	**Mass of honey (mg)**
15	58.4
25	67.0
35	75.7
At shade	
15	65.0
25	64.6
35	64.3

Table 3.3. Work performed by 3,000 honeybees during the production of 1 kg honey when 0.5 M of unlimited sucrose flow was available

Under the sunshine at atmospheric pressure; U = 0.0 m/s		**At shade, under the atmospheric pressure U = 0.0 m/s**
T_a (°C)	**Q**	**Q**
15	-3,224	-1,902
25	2,655	2,001
35	9,012	6,102
Under the sunshine at atmospheric pressure; U = 0.5 m/s		At shade, under atmospheric pressure; U = 0.5 m/s
15	1,995	2,749
25	5,429	4,625
35	9,789	6,130
Under the sunshine at atmospheric pressure; U = 1m/s		At shade, under at atmospheric pressure; U = 1 m/s
15	3,591	4,171
25	6,269	5,417
35	10,022	6,138

3.2. EVAPORATION OF WATER

Honeybees evaporate metabolic water to prevent overheating. Evaporation rate of metabolic water by the foraging honeybees decreases at high T_a due to the low rate of metabolism. The increase in the rate of water evaporated by the foraging honeybees parallels to the rate of sucrose consumption and heat up take. In the present study, the minimum evaporation rate was 8.5 $x10^{-6}$ g/min under the sunshine at 35^{o}C when honeybees were fed with 15 µl/min of 0.5 M sucrose and the maximum evaporation rate of the metabolic water was 1.4 $x10^{-4}$ g/min under the sunshine at 15^{o}C when the honeybees were fed with 0.5 M of unlimited sucrose flow (Table 2.1). Additionally, the foraging honeybees consumed water within the range of 1.21 $x10^{-4}$ g/min (the maximum) and 7.99 $x10^{-6}$ g/min (the minimum) in order to compensate evaporation of metabolic water (Table 2.1). Water uptake at 15, 25 and 35°C by the foraging honeybees depending on the oxygen consumption and carbon dioxide production at shade and under the sunshine with 0.5 M of sucrose supply with 15 µl/min of flow rate and with 0.5 M of unlimited sucrose supply were described in Figures A6 and A7, respectively.

Rate of metabolic water output depends on the rates of sucrose and the total heat up takes. The rate of evaporation of water by the 1-7 h young resting honeybees increased at high ambient temperatures. The minimum amount of water evaporated was 7.1 $x10^{-7}$g/min at 15^{o}C and the maximum amount was 2.1 $x10^{-6}$ g/min at 35ºC (Table 2.1). The rate of evaporation of water by the foraging honeybees was higher than that of a 1-7 h old young resting honeybees, since the foraging honeybees may get overheated due to its activity and total heat up take from the environment, when compared to the others. The young resting honeybees needed between 6.3 $x10^{-7}$ g/min (the minimum) and 1.9 $x10^{-6}$ g/min (the maximum) of additional to compensate the loss of metabolic water (Table 2.1).

3.3. THE RATES OF HEAT EXCHANGE

Solar radiation supplies the energy needed for the thermoregulation of foraging bees [102]. The maximum and the minimum convective heat losses were 0.051 and 0.002 W under the sunshine, with 1.0 m/s of air speed and at 15^{o}C with 0.0 m/s of air speed at 35^{o}C, respectively. Convective heat transfer rate at 0.0 m/s of velocity corresponds to the natural convective heat transfer at same conditions (Table 3.7). Calculations of the metabolic heat production agrees with the report that the rate of the metabolism of a flying honeybee decreases significantly with rising ambient temperature [58,59]. Convective heat losses increase with air speed and decrease with increase in the ambient temperature. Figures A2, A3, A4, and A5 show the interrelation between heat transfer rate and air velocity and ambient temperature. When T_a was lower than 15^{o}C, a reduction in convective heat loss might be achieved by intermittent warm - up following intermittent flight [62].

Radiative heat exchange is related with the exposure to direct sunshine - it may be huge under the direct sunlight or may be slight in the shadow. In the present study, solar radiation was the maximum at 35^{o}C, it was 453.3 W/m^2 for incoming radiation and 510.3 W/m^2 for outgoing radiation with the contribution of the long and short wavelengths (Table 3.5). In the shadow, radiative heat losses were similar in magnitude to the convective heat losses in still air and were also dependent on the difference between the body temperature of the honeybees and the air temperature[62]. During resting, honeybee does not benefit from the solar radiation, where also the natural convective heat transfer and the forced convection heat transfer almost never occur. The 1-7 h old young resting honeybees benefited only from their metabolic heat.

Table 3.4. Total heat lost by the foraging honeybees with convection under the sunshine and at shade, at 15, 25 and 35°C

Under the sun shine, under the atmospheric pressure, with 0.5 M of sucrose supply with 15 µl/min flow rate; U = 0.0 m/s		**At shade, under the atmospheric pressure, with 0.5 M of sucrose supply with 15 µl/min flow rate; U = 0.0 m/s**
T_a (°C)	**Q (W)**	**Q (W)**
15	0.017	0.015
25	0.0082	0.015
35	0.0020	-
Under the sun shine, at atmospheric pressure, with 0.5 M of unlimited sucrose supply; U = 0.0 m/s		At shade, under the atmospheric pressure, with 0.5 M of unlimited sucrose supply; U = 0.0 m/s
15	0.0031	0.0041
25	0.014	0.015
35	0.021	0.0022
Under the sun shine, under the atmospheric pressure, with 0.5 M of sucrose supply with 15 µl/min flow rate; U = 0.5m/s		At shade, under the atmospheric pressure, with 0.5 M of sucrose supply with 15 µl/min flow rate; U = 0.5 m/s
15	0,043	0.039
25	0,022	0.028
35	0,0066	-
Under the sun shine, under the atmospheric pressure with 0.5 M of unlimited sucrose supply; U=0.5 m/s		At shade, under the atmospheric pressure with 0.5 M of unlimited sucrose supply; U = 0.5 m/s
15	0.032	0.032
25	0.032	0.030
35	0.03	0.0023
Under the sun shine, under the atmospheric pressure, with 0.5 M of sucrose supply with 15 µl/min flow rate; U = 1.0 m/s		At shade, under the atmospheric pressure, with 0.5 M of sucrose supply with 15 µl/min flow rate; U = 1.0 m/s
15	0.051	0.046
25	0.026	0.032
35	0.01	-
Under the sun shine, under the atmospheric pressure, with 0.5 M of unlimited sucrose supply; U=1.0 m/s		At shade, under the atmospheric pressure, with 0.5 M of unlimited sucrose supply; U=1.0 m/s
15	0.040	0.041
25	0.037	0.035
35	0.028	0.0024

Table 3.5. Power of the incoming and outgoing radiation at 15, 25 and 35°C

T_a (°C)	**Incoming radiation (W/m^2)**	**Outgoing radiation (W/m^2)**
15	303	309.08
25	371.87	477.15
35	453.31	510.25

The limiting conditions where the honeybees can survive are described in Table 3.6. Habitat dynamics are affected by the environmental conditions imposed by the climate change [103]. Honeybee colony mortality is affected by the change in the nature of the parasites, diseases, pesticides and the availability of nutrients [104]. With the increase of T_a both use of the pesticides to protect the agricultural products from parasites increases and also new pesticides are employed to fight against the new plant pests emerging with the climate change [105]. Honeybees foraging near the agricultural fields are exposed to these pesticides. It was stated that more than 62 per cent of the pollens collected by the honeybees in Italy during the time period of 2012 to 2014 were contaminated by at least one pesticide [106] showing that how serious this problem is. The unsuitable whether conditions may cause honeybee migration, during which parasites may also be transported to the area that the honeybees have migrated. However, the change of the conditions may also lead to unexpected response of the honeybees. Short-term starvation during larval stages increases the probability of the survival of the adult bees under starvation and change their metabolic response to starvation [107]. *Varroa destructor*, an ectoparasitic mite, is a classic example of a pest that has shifted from *Apis cerena*, Asian honeybee to the European honeybee *Apis mellifera* [108]. The changing temperatures that the honeybee colonies are possibly exposed throughout a day can be particularly hard to buffer against [109]. High temperatures outside the hive are balanced by carrying water into the hive and evaporating this by wing fanning. Low temperatures inside the hive are compensated by the production of heat through thoracic muscle activity of the worker bees [110]. The fanning energy requirement increases at high T_a [111]. Honeybees heated the hive by 1°C in 2.8 min and cooled the hive by 1°C in 2.12 min. Metabolic heat required to raise the temperature of the hive by 1°C was 7.25×10^{-4} W/g honeybee. However, the amount of metabolic heat required to reduce the temperature of the hive by 1°C was 3.08×10^{-3} W/g honeybee. The number of the honeybees in a colony is important. During ventilation of air, as the number of honeybees present in the colony increases, metabolic heat required to be produced by each honeybee decreases.

Table 3.6. Range of the physical parameters, where the honeybees may survive

Foraging/ resting	**Under the sunshine /shade**	**T_a (ºC)**	**Rate of metabolism (W/g honeybee)**	**Rate of sucrose consumption (g/min)**	**Rate of O_2 uptake (g/min)**	**Rate of CO_2 generation (g/min)**	**Velocity of flight (m/s)**
Foraging	Sunshine	15	0.03	4.4×10^{-4}	2.4×10^{-4}	3.4×10^{-4}	0.0
Foraging	Sunshine	35	0.51	2.7×10^{-5}	1.5×10^{-5}	2.1×10^{-5}	0.5
Resting	Hive	15	2.7×10^{-3}	2.3×10^{-6}	1.3×10^{-6}	1.7×10^{-6}	1
Resting	Hive	35	7.7×10^{-3}	6.6×10^{-6}	3.7×10^{-6}	5.1×10^{-6}	-

3.4. FANNING POWER

Honeybees heated the hive by 1ºC in 2.8 min and cooled it by 1ºC in 2.12 min. Metabolic heat required to raise the temperature of the hive by 1ºC was 7.25×10^{-4} W/g honeybee. However, the amount of metabolic heat required to reduce the temperature of the hive by 1ºC was 3.08×10^{-3} W/g honeybee. The rate of metabolism was presented in Table 3.7. The worker honeybees are 12 to 16 mm in size [112]. Their pictures imply that the open wings may clear a circular area of same diameter as their length. A chain of three honeybees may move air at a velocity of 2.24 m/s [113] . Therefore, the air removal rate of a string of honeybees during fanning may be calculated as $\dot{V} = \pi \left(\frac{d_{honeybee}}{2}\right)^2 v_{air} = 2.8\ 10^{-5}\ m^3/s$. When there are 3,000 workers in the hive, the total amount of air fanned will be 0.082 m^3/s, and it will take 36 s to fan 1 m^3 air out of the hive. On the other hand, honeybees generate 4.8×10^{-6} and 1.2×10^{-5} W/g honeybee K of entropy while raising and reducing the temperature of hive, respectively during ventilation.

When 3,000 honeybees were in the hive, they performed 3.17 kJ/kg dry air of work, generated 4.44 kJ/kg dry air of heat and 161.6 W/g K of entropy while raising the temperature of the hive by 1ºC (Table 3.8). However, they performed 4.5 kJ/kg dry air honeybee of work, generated 7.27 kJ/kg dry air of heat and 308.9 W/g K of entropy while reducing the temperature of the hive by 1°C.

Table 3.7. Rates of metabolism during ventilation of air

T_a (K)	Rate of metabolic heat production (W/g honeybee)
296.89	0.0362
297.36	0.0364
297.78	0.0362
298.14	0.0350

3.5. ENTROPY GENERATION

Entropy generation rate by the foraging honeybees was the minimum, 1.8×10^{-5} W/g honeybee K, under the sunshine with 15 µl/min of 0.5 M sucrose in flow (Table 3.8). The second law of thermodynamics, implies that a thermodynamic system operates better it generates less entropy [89]. Therefore, the best condition for the honeybees to forage was foraging under the sunshine with inflow of 15 µl/min of 0.5 M sucrose. However, with the foraging honeybees, the maximum entropy generation rate was 6.6×10^{-5} W/g honeybee K at shade with unlimited supply of sucrose and these conditions are not suitable for foraging honeybees. Entropy generation rate of the 1-7 h old young resting honeybees was 1.2×10^{-7} W/g honeybee K under the atmospheric pressure with 0.5 M of sucrose supply at 15 µl/min flow rate. Entropy generation rate by the honeybees under three different conditions is presented in Table 3.8.

Table 3.8. Entropy generation by the honeybees

	$S_{gen,}$
While foraging under the sun shine, under the atmospheric pressure with 0.5 M of sucrose supply with 15 µl/min flow rate	1.8 x10^{-5} (W/g honeybee K)
While foraging at shade, under the atmospheric pressure with 0.5 M of sucrose supply with 15 µl/min flow rate	3.8 x10^{-5} (W/g honeybee K)
While foraging under the sun shine, under the atmospheric pressure with 0.5 M of unlimited sucrose supply	6.6 x10^{-5} (W/g honeybee K)
While foraging at shade, under the atmospheric pressure with 0.5 M of unlimited sucrose supply	7.2 x10^{-5} (W/g honeybee K)
While resting under atmospheric pressure, with 0.5 M of sucrose supply at 15 µl/min flow rate	1.2 x10^{-7} (W/g honeybee K)
While raising the temperature of the hive by 1 ºC during air ventilation	4.8 x10^{-6} (W/g honeybee K)
While reducing temperature of the by 1ºC during air ventilation	1.2 x10^{-5} (W/g honeybee K)
During the production of honey under the sun shine, under the atmospheric pressure with 0.5 M of unlimited sucrose supply	116.5 (kJ/day K kg honey)
During the production of honey at shade, under the atmospheric pressure with 0.5 M of unlimited sucrose supply	132.2 (kJ/day K kg honey)

4. CONCLUSION

Honeybees are among the most sensitive biological species to the changes in environmental conditions. Since pollination is necessary for the cultivation of more than 75 per cent of the crops used directly by the people worldwide, any injury to the honeybee population due to the climate change may jeopardize the food security. Therefore, thermodynamic parameters which are implemented on the honeybees under the prevailing environmental conditions and which may be implemented in the case of an anticipated temperature change were assessed. According to our calculations, 0.032 W/g honeybee was the maximum metabolic heat produced under the sunshine at 15°C and with unlimited sucrose flow. However, the minimum metabolic heat produced by the foraging honeybees was 2.0 x 10^{-3} W/g honeybee under the sunshine at 35°C with 0.5 M of sucrose supply at 15 µl/min flow rate. Metabolic heat produced by a foraging honeybee changes with the rate of the sucrose supply and T_a. Under the sunshine, the maximum and the minimum fraction, e.g. amount metabolized per amount collected, 0.27 per cent and 0.067 per cent, were accounted during foraging with unlimited sucrose supply at 15 and 35°C, respectively. A group of 3,000 honeybees performed 10,022 kJ/kg day of work under the sunshine with 1.0 m/s of air velocity or -3,224 kJ/kg day at 0.0 m/s air velocity to produce 1 kg honey. In addition, they generated 116.5 kJ/day K of entropy under sunshine and 132.2 kJ/day K of entropy at shade. The work performed by the honeybees increased with the air velocity. The maximum entropy generation, 7.2 x10^{-5} W/g honeybee K, was accounted during foraging at 35°C at shade with 0.5 M of unlimited sucrose supply. With 3,000 honeybees, work performance was 3.17 kJ/kg dry air, heat generation was 4.44 kJ/kg dry air and the entropy generation was 161.6 W/g honeybee K while raising the temperature of the hive by 1°C. On the other hand, they have to perform 4.5 kJ/kg dry air of work, generate 7.27 kJ/kg dry air of heat and 308.9 W/g honeybee K of entropy to reduce the temperature of the hive by 1°C. The results show that during cooling by 1°C the honey bees performed 1.4 folds of work and generated 1.9 folds of entropy when compared to that of heating by 1°C.This result implies that global warming will possibly create 90 per cent more entropy stress on the honeybees when compared to a potential global cooling.

REFERENCES

1. Morelli J. Environmental sustainability: a definition for environmental professionals. *J Environ Sustain.* 2011;1:1–10.

2. Moldan B, Janoušková S, Hák T. How to understand and measure environmental sustainability: indicators and targets. *Ecol Indic*. 2012;17:4–13.

3. Vlek CAJ, Steg L. Human behavior and environmental sustainability: problems, driving forces, and research topics. *J Soc Issues*. 2007; 63:1–19.

4. Karl TR, Melillo JM, Peterson TC, Hassol SJ. *Global climate change impacts in the united states*. New York: Cambridge University Press; 2009.

5. Wolff E, Fun I, Hoskins B, Mitchell J, Palmer T, Santer B, Shepherd J, Shine K, Solomon S, Trenberth K, et al. Climate change evidence & causes. *Natl Acedemy Sci.* 2014.

6. NASA. Climate change and global warming. [cited 2018 18 Jun]. Available from: https://climate.nasa.gov/

7. UNFCCC. Climate change: impacts, vulnerabilities and adaptation in developing countries. *United Nations Framew Conv Clim Chang;* 2007.

8. Henderson RM, Reinert SA, Dekhtyar P, Migdal A. Climate change in 2017: implications for business. *Harvard Bus Sch*. 2017;1-39.

9. Schneider N. *Understanding climate change.* British Colombia: The Fraser Institute; 2008.

10. Carey J. Global warming: faster than expected? *Sci Am*. 2012;307:50–55.

11. IPCC. Climate Change 2014 Synthesis Report Summary Chapter for Policymakers. *Ipcc*. 2014;1-31.

12. Mann ME, Bradley RS, Hughes MK. Global-scale temperature patterns and climate forcing over the past six centuries. *Nature*. 1998;392:779–787.

13. Jian-Bin H, Shao-Wu W, Yong L, Zong-Ci Z, Xin-Yu W. The Science of global

warming. *Adv Clim Chang Res*. 2012;3:174–178.

14. Michaels P. Global warming- climate change. *Cato Handbook for Policymakers*. 2009;475-85.

15. Jian-Bin H, Shao-Wu W, Yong L, Zong-Ci Z, Xin-Yu W. Debates on the causes of global warming. *Adv Clim Chang Res*. 2012;3:38–44.

16. Parry M, Palutikof J, Adger N, Agrawala S, Alcamo J, Cramer W, Murdiyarso D. A report accepted by Working Group II of the Intergovernmental Panel Technical Summary. *IPCC*. 2007;23-78.

17. Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE. Summary for Policymakers. *Clim Chang 2007 Impacts, Adapt Vulnerability Contrib of Working Gr II to Fourth Assess Rep Intergov Panel Clim Chang*. 2007;7-22.

18. Shahzad U. Global warming : causes , effects and solutions. *Durreesamin Journal*. 2007;(4):1-7.

19. IPCC. Socio-economic data and scenarios. [cited 2018 7 Jun]. Available from: http://sedac.ipcc-data.org/ddc/observed/index.html

20. Wang S, Wen X, Luo Y, Tang G, Zhao Z, Huang J. Does the global warming pause in the last decade: 1999–2008? *Adv Clim Chang Res*. 2010;1:49–54.

21. Aizebeokhai AP. Global warming and climate change : realities , uncertainties and measures. *Int J Phys Sci*. 2009;4:868–879.

22. Winston ML. *The biology of the honeybee*. Cambrige: Harvard University Press; 1987.

23. Pettis JS, Rice N, Joselow K, Van Engelsdorp D, Chaimanee V. Colony failure linked to low sperm viability in honey bee (*Apis mellifera*) queens and an exploration of potential causative factors. *PLoS One*. 2016;11:1–10.

24. N. Mortensen A, R. Schmehl D, Ellis J: European honey bee - *Apis mellifera*. *IFAS Extension University of Florida*. 2013;1-6.

25. Shi YY, Huang ZY, Zeng ZJ, Wang ZL, Wu XB, Yan WY. Diet and cell size both

affect queen-worker differentiation through DNA methylation in honey bees (*Apis mellifera*, apidae). *PLoS One*. 2011;6:2–7.

26. Kamakura M. Royalactin induces queen differentiation in honeybees. *Nature.* 2011;473:478–483.

27. Yang W, Tian Y, Han M, Miao X. Longevity extension of worker honey bees (*Apis mellifera*) by royal jelly: optimal dose and active ingredient. *PeerJ* . 2017;5:e3118.

28. Cramp D. *A practical manual of beekeeping: how to keep bees and develop your full potential as an apiarist*. Oxford: Spring. 2008.

29. Winston ML. *The biology of the honey bee*. Cambrige: Harvard University Press; 1987.

30. Yadav S, Kumar Y, Jat BL. Honeybee: diversity, castes and life cycle. *Industrial Entomology*. 2017;5-33.

31. Seeley TD. *Honeybee democracy*. New Jersey: Princeton University Press; 2010.

32. Page RE, Peng CYS. Aging and development in social insects with emphasis on the honey bee, *Apis mellifera L. Exp Gerontol.* 2001;36:695–711.

33. Hamdan K, Apeldoorn. Bee colony activities throughout the year bee colony : basic facts. [cited 2018 15 June] Available from: http://countryrubes.com/template/images/ee_Colony_Activities_Throughout_The_Year_updated_09_09.pdf.

34. Somerville D. Bee swarms and their control. *Agnote*. 1999;125:1-2.

35. Van Der Zee R, Gray A, Pisa L, De Rijk T. An observational study of honey bee colony winter losses and their association with *Varroa destructor*, neonicotinoids and other risk factors. *PLoS One*. 2015;10:1–25.

36. Kilani M. Biology of the honeybee. *Bee Dis Diagnosis*. 1999;24:9–24.

37. Waller BGD. Honey bee life history. [cited 2018 14 June] Available from: https://beesource.com/resources/usda/honey-bee-life-history/

38. Otis GW, Wheeler DE, Buck N, Mattila HR. Storage proteins in winter honeybees. *Apiacata*. 2004;38:352–357.

39. Wineman E, Lensky Y, Mahrer Y. Solar heating of honey bee colonies (*Apis mellifera L.*) during the subtropical winter and its impact on hive temperature, worker population and honey production. *Am Bee J.* 2003;143:565–570.

40. Stabentheiner A. Endothermic heat production in honeybee winter clusters. *J Exp Biol*. 2003;206:353–358.

41. Silva DP, Moisan-De-Serres J, Souza DC, Hilgert-Moreira SB, Fernandes MZ, Kevan PG, Freitas BM. Eficiency in pollen foraging by honey bees: time, motion, and pollen depletion on flowers of *Sisyrinchium palmifolium* (Asparagales: Iridaeae). *J Pollinat Ecol.* 2013;11:27–32.

42. Eyer M, Dainat B, Neumann P, Dietemann V. Social regulation of ageing by young workers in the honey bee, Apis mellifera. *Exp Gerontol.* 2017;87:84–91.

43. Okada R, Akamatsu T, Iwata K, Ikeno H, Kimura T, Ohashi M, Aonuma H, Ito E. Waggle dance effect: dancing in autumn reduces the mass loss of a honeybee colony. *J Exp Biol.* 2012; 215:1633–1641.

44. Esch H, Goller F, Burns JE. Honeybee waggle dances: the “energy hypothesis” and thermoregulatory behavior of foragers. *J Comp Physiol B.* 1994;163:621–625.

45. Schürch R, Ratnieks FLW, Samuelson EEW, Couvillon MJ. Dancing to her own beat: honey bee foragers communicate via individually calibrated waggle dances. *J Exp Biol.* 2016;219:1287–1289.

46. Hepburn HR, Radloff SE. *Honeybees of asia*. Berlin:Springer; 2011.

47. Tautz J. Honeybee waggle dance: recruitment success depends on the dance floor. *J Exp Biol.* 1996;1381:1375–1381.

48. Sagili RR, Pankiw T. Effects of protein-constrained brood food on honey bee (*Apis mellifera L.*) pollen foraging and colony growth. *Behav Ecol Sociobiol.* 2007;61:1471–1478.

49. Nagai T, Nagashima T, Suzuki N, Inoue R. Antioxidant activity and angiotensin I-converting enzyme inhibition by enzymatic hydrolysates from bee bread. *Zeitschrift fur Naturforsch - Sect C J Biosci.* 2005;60:133–138.

50. Künast PDC, Riffel DM, Graeff R de, Whitmore G. Pollinators and agriculture. In *Pollinators and Agriculture*. 2013;1–3.

51. Memmott J, Craze PG, Waser NM, Price M V. Global warming and the disruption of plant-pollinator interactions. *Ecol Lett.* 2007;10:710–717.

52. Aronne G, Giovanetti M, Guarracino MR, de Micco V. Foraging rules of flower selection applied by colonies of *Apis mellifera*: ranking and associations of floral sources. *Funct Ecol.* 2012;26:1186–1196.

53. Corbet SA, Willimas IH, Osborne JL. Bees and the polllination of crops and wild flowers: changes in the European community. *Bee World.* 1991;72:47–59.

54. Suwannapong G, Eiri DM, Benbow ME. Honeybee communication and pollination. *New Perspect Plant Prot*. 1998:39-62.

55. Dağaşan HY, Özdoğan AO, Kaftanouglu O. Comparison of honey bees (*Apis mellifera L.*) and bumble bees (*Bombus terrestris*) as pollinators for melon (*Cucumis melo L.*) grown in greenhouses. *Proc. 1st Int. Symp. on Cucurbits*. Turkey; 1999. p.492.

56. Sparks TH, Langowska A, Głazaczow A, Wilkaniec Z, Bieńkowska M, Tryjanowski P. Advances in the timing of spring cleaning by the honeybee *Apis mellifera* in Poland. *Ecol Entomol*. 2010, 35:788–791.

57. Stabentheiner A, Vollmann J, Kovac H, Crailsheim K. Oxygen consumption and body temperature of active and resting honeybees. *J Insect Physiol.* 2003;49:881–889.

58. Harrison JF, Fewell JH, Roberts SP, Hall HG. Achievement of thermal stability by varying metabolic heat production in flying honeybees. *Science.* 1996;274:88–90.

59. Roberts S, Harrison J. Mechanisms of thermal stability during flight in the honeybee apis mellifera. *J Exp Biol*. 1999;202(11):1523–33.

60. Kovac H, Stabentheiner A, Schmaranzer S. Thermoregulation of water foraging honeybees-balancing of endothermic activity with radiative heat gain and functional requirements. *J Insect Physiol.* 2010;56:1834–1845.

61. Kovac H, Käfer H, Stabentheiner A, Costa C. Metabolism and upper thermal limits

of *Apis mellifera carnica* and *A. m. ligustica*. *Apidologie.* 2014;45:664–677.

62. Moffatt L. Metabolic rate and thermal stability during honeybee foraging at different reward rates. *J Exp Biol*. 2001;204:759–766.

63. Seeley TD. Atmospheric carbon dioxide regulation in honey-bee (*Apis mellifera*) colonies. *J Insect Physiol.* 1974;20:2301–2305.

64. Lighton JRB, Lovegrove BG. A temperature-induced switch from diffusive to convective ventilation in the honeybee. *J Exp Biol.* 1990;154:509–516.

65. Gordo O, Sanz J. Temporal trends in phenology of the honey bee *Apis mellifera* and the small white *Pieris rapae* in the Iberian Peninsula (1952–2004). *Ecol Entomol*. 2006; 31:261–268.

66. Reddy PVR, Verghese A, Rajan VV. Potential impact of climate change on honeybees (Apis spp.) and their pollination services. *Pest Manag Hortic Ecosyst.* 2012;18:121–127.

67. Giannini TC, Acosta AL, Garófalo CA, Saraiva AM, Alves-dos-Santos I, Imperatriz-Fonseca VL. Pollination services at risk: bee habitats will decrease owing to climate change in Brazil. *Ecol Modell.* 2012;244:127–131.

68. Ogilvie JE, Griffin SR, Gezon ZJ, Inouye BD, Underwood N, Inouye DW, Irwin RE. Interannual bumble bee abundance is driven by indirect climate effects on floral resource phenology. *Ecol Lett.* 2017;20:1507–1515.

69. Guler A, Kaftanoglu O. Determination of performances some important races and ecotypes of Turkish honeybees (*Apis mellifera L.*) under migratory beekeeping conditions. *Turkish J Vet Anim Sci.* 1999;23:577–581.

70. Lindsey R. Buzzing about climate change : feature articles 2007. [cited 2007 10 March]. Available from: http://earthobservatory.nasa.gov/Features/Bees/bees4.php

71. Morton EM, Rafferty NE. Plant–pollinator interactions under climate change: the use of spatial and temporal transplants. *Appl Plant Sci*. 2017;5:1600133.

72. Willmer P. Climate change: bees and orchids lose touch. *Curr Biol.* 2014;24:R1133–R1135.

73. Kurnaz L, Şahin Ü. İklim değişikliği ve kuraklık 2014. [cited 2018 10 March] Available from: https://www.researchgate.net/publication/316190182.

74. Scaven VL, Rafferty NE. Physiological effects of climate warming on flowering plants and insect pollinators and potential consequences for their interactions. *Curr Zool*. 2013;59:418–426.

75. Hegland SJ, Nielsen A, Lázaro A, Bjerknes AL, Totland Ø. How does climate warming affect plant-pollinator interactions? *Ecol Lett*. 2009;12:184–195.

76. Wang Y, Kaftanoglu O, Brent CS, Page RE, Amdam G V. Starvation stress during larval development facilitates an adaptive response in adult worker honey bees (*Apis mellifera* L.). *J Exp Biol*. 2016;219:949–959.

77. Le Conte Y, Navajas M. Climate change: impact on honey bee populations and diseases. *Rev Sci Tech*. 2008;27:485–497, 499–510.

78. Paudel YP, Mackereth R, Hanley R, Qin W. Honey bees (*Apis mellifera L*.) and pollination issues: current status, impacts and potential drivers of decline. *J Agric Sci*. 2015;7:93–109.

79. Zoltowska K, Frączek R, Lipiński Z. Hydrolases of developing worker brood and newly emerged worker. *J Apic Sci*. 2011;55:27–37.

80. Roberts SP, Harrison JF. Mechanisms of thermoregulation in flying bees. *Integr Comp Biol*. 1998;38:492–502.

81. Humphrey JAC, Dykes ES. Thermal energy conduction in a honey bee comb due to cell-heating bees. *J Theor Biol*. 2008;250:194–208.

82. Stabentheiner A, Kovac H. Honeybee economics: optimisation of foraging in a variable world. *Sci Rep*. 2016;6:1–7.

83. Mahan BH. *University chemistry*. California: Addison-Wesley Pub. Co; 1965.

84. FAO. Food energy – methods of analysis and conversion. *FAO Food Nutr Pap*. 2002; 3:93.

85. Feinman RD, Fine EJ. “A calorie is a calorie” violates the second law of

thermodynamics. *Nutr J.* 2004;3:1–5.

86. Henriquesa IB, Madyb CEK, de Oliveira S. Exergy model of human heart. *The 28th International Conference on Efficiency, Costs, Optimization, Simulation and Environmental Impact of Energy Systems*; 2015;1-8.

87. Kabo GJ, Voitkevich O V., Blokhin A V., Kohut S V., Stepurko EN, Paulechka YU. Thermodynamic properties of starch and glucose. *J Chem Thermodyn.* 2013;59:87–93.

88. Morrison SD. A method for the calculation of metabolic water. *J Physiol.* 1953;122:399–402.

89. Kuddusi L. Thermodynamics and life span estimation. *Energy*. 2015;80:227–238.

90. Moran MJ, Shapiro HN. Index to Tables in SI Units. *Fundamentals of engineering thermodynamics.* John Wiley & Sons. 2006:718-281.

91. Goldberg RN, Tewari YB, Ahluwalia JC. Thermodynamics of the hydrolysis of sucrose. *J Biol Chem.* 1989;264:9901–9904.

92. Stabentheiner A, Kovac H. Energetic optimisation of foraging honeybees: flexible change of strategies in response to environmental challenges. *PLoS One.* 2014;9(8).

93. Cooper PD, Schaffer WM, Buchmann SL. Temperature regulation of honey bees (*Apis mellifera*) foraging in the Sonoran Desert. *J exp Biol.* 1985;114:1–15.

94. Cengel Y. *Heat transfer: a pratical approach*. New York: McGraw - Hill; 2002.

95. Southwick EE, Moritz RFA. Social control of air ventilation in colonies of honey bees, *Apis mellifera*. *J Insect Physiol.* 1987;33:623–626.

96. Toledo RT. Refrigeration. *Fundamentals of Food Process Engineering*; 2007:379–412.

97. FLSmidth. Specific Heat capacities and Individual Gas Constants. [cited 2018 20 April]. Avalabile from http:// catalog.conveyorspneumatic.com /Asset / FLS%20Specific%20Heat%20Capacities%20of%20Gases.pdf. 2009.

98. Silva CA, Annamalai K. Entropy generation and human aging: lifespan entropy and

effect of diet composition and caloric restriction diets. *J Thermodyn.* 2009;2009:1–10.

99. Değerli B, Küçük K, Sorgüven E, Özilgen M. Thermodynamic analysis of serogroup C antigen production by *Neisseria meningitidis*. *Int J Exergy.* 2015;16:1–21.

100. Hall JE. *Guyton and Hall textbook of medical physiology*. London: Elsevier; 2016.

101. Kovac H, Stabentheiner A, Hetz SK, Petz M, Crailsheim K. Respiration of resting honeybees. *J Insect Physiol.* 2007;53:1250–1261.

102. Heinrich B. Thermoregulation of African and European honeybees during foraging, attack, and hive exits and returns. *J exp Biol.* 1979;80:217–229.

103. Hernando MD, Gámiz V, Gil-Lebrero S, Rodríguez I, García-Valcárcel AI, Cutillas V, Fernández-Alba AR, Flores JM. Viability of honeybee colonies exposed to sunflowers grown from seeds treated with the neonicotinoids thiamethoxam and clothianidin. *Chemosphere.* 2018.

104. Switanek M, Crailsheim K, Truhetz H, Brodschneider R. Modelling seasonal effects of temperature and precipitation on honey bee winter mortality in a temperate climate. *Sci Total Environ.* 2017;579:1581–1587.

105. Gómez-Ramos M del M, Gómez Ramos MJ, Martínez Galera M, Gil García MD, Fernández-Alba AR. Analysis and evaluation of (neuro)peptides in honey bees exposed to pesticides in field conditions. *Environ Pollut.* 2018;235:750–760.

106. Tosi S, Costa C, Vesco U, Quaglia G, Guido G. A 3-year survey of Italian honey bee-collected pollen reveals widespread contamination by agricultural pesticides. *Sci Total Environ.* 2018;615:208–218.

107. Wang Y, Campbell JB, Kaftanoglu O, Page RE, Amdam G V. Harrison JF. Larval starvation improves metabolic response to adult starvation in honey bees (*Apis mellifera L.*). *J Exp Biol*. 2016;219:960–968.

108. Chantawannakul P, Ramsey S, vanEngelsdorp D, Khongphinitbunjong K, Phokasem P. Tropilaelaps mite: an emerging threat to European honey bee. *Curr Opin Insect Sci.* 2018;26:69–75.

109. Cook CN, Kaspar RE, Flaxman SM, Breed MD. Rapidly changing environment modulates the thermoregulatory fanning response in honeybee groups. *Anim Behav.* 2016;115:237–243.

110. Tautz J, Maier S, Groh C, Rössler W, Brockmann A. Behavioral performance in adult honey bees is influenced by the temperature experienced during their pupal development. *Proc Natl Acad Sci.* 2003;100:7343–7347.

111. Egley RL, Breed MD. The fanner honey bee: behavioral variability and environmental cues in workers performing a specialized task. *J Insect Behav.* 2013:26:238–245.

112. Species *Apis mellifera* - Western Honey Bee. [cited 2018 30 Apr]. Available from: https://bugguide.net/node/view/3080

113. Junge M. Fanning in honey bees - a comparison betweenmeasurement and calculation of non-stationaryaerodynamic forces. *WIT Trans State-of-the-art Sci Eng*. 2006; 3.

114. Chapter 10b: The Psychrometric Chart 2014. [cited 2018 23 Apr]. Available from:https://www.ohio.edu/mechanical/thermo/Applied/Chapt.7_11/
Chapter10b.html

APPENDIX A: FIGURES

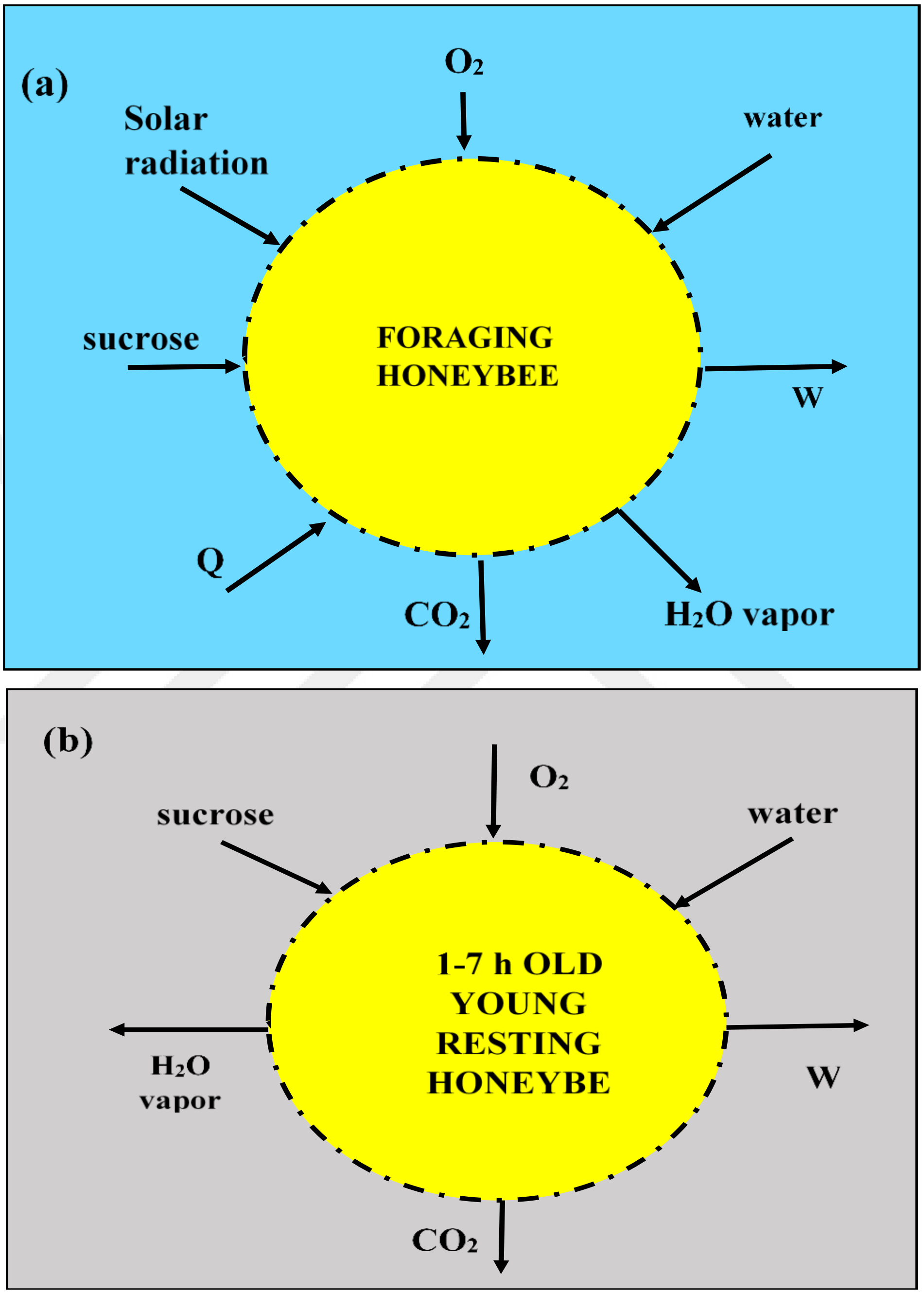

Figure A.1. Schematic description of the (a) foraging and (b) 1-7 h old young resting honeybees as an open thermodynamic system

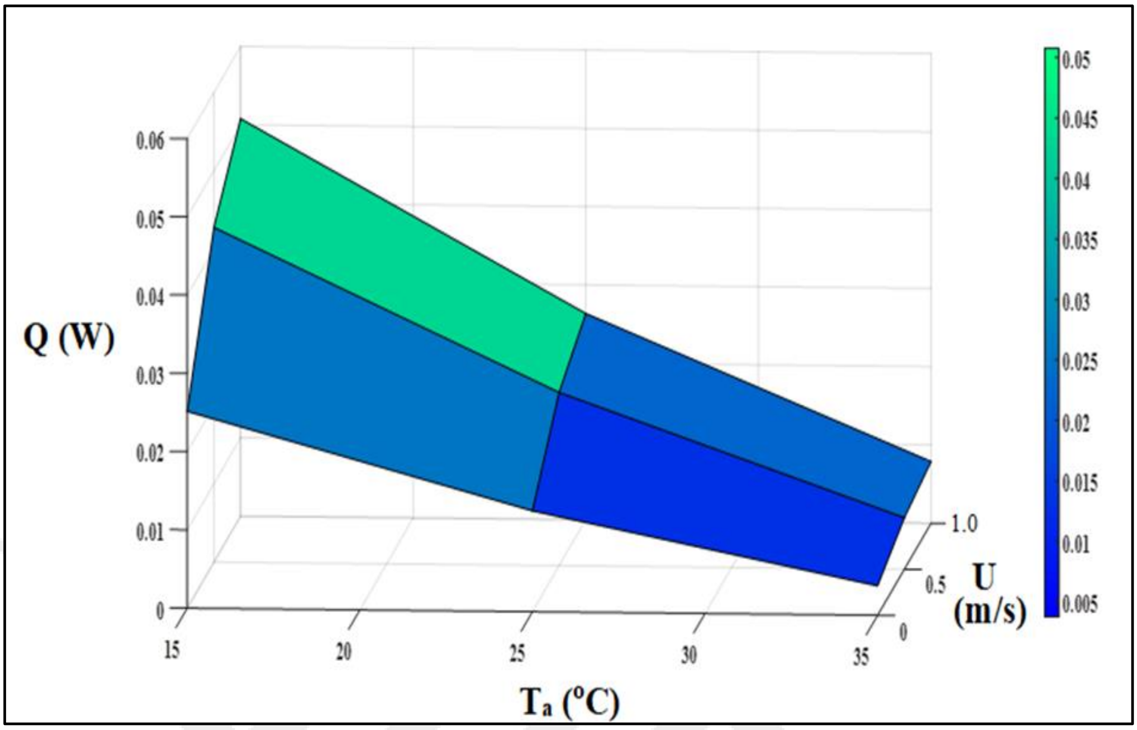

Figure A.2. Variation of the heat lost by the foraging honeybees with the air velocity and the atmospheric temperature under the sunshine when 0.5 M of sucrose is supplied at 15 μl/min of flow rate

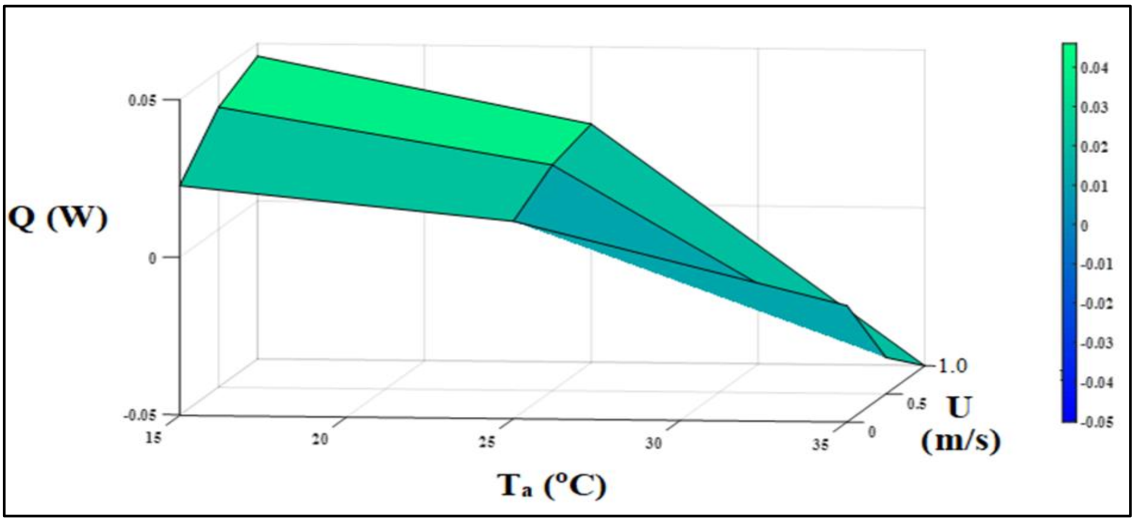

Figure A.3. Heat lost by the foraging honeybees depending on the air velocity and the atmospheric temperature at shade with 0.5 M of sucrose supply at 15 μl/min flow rate

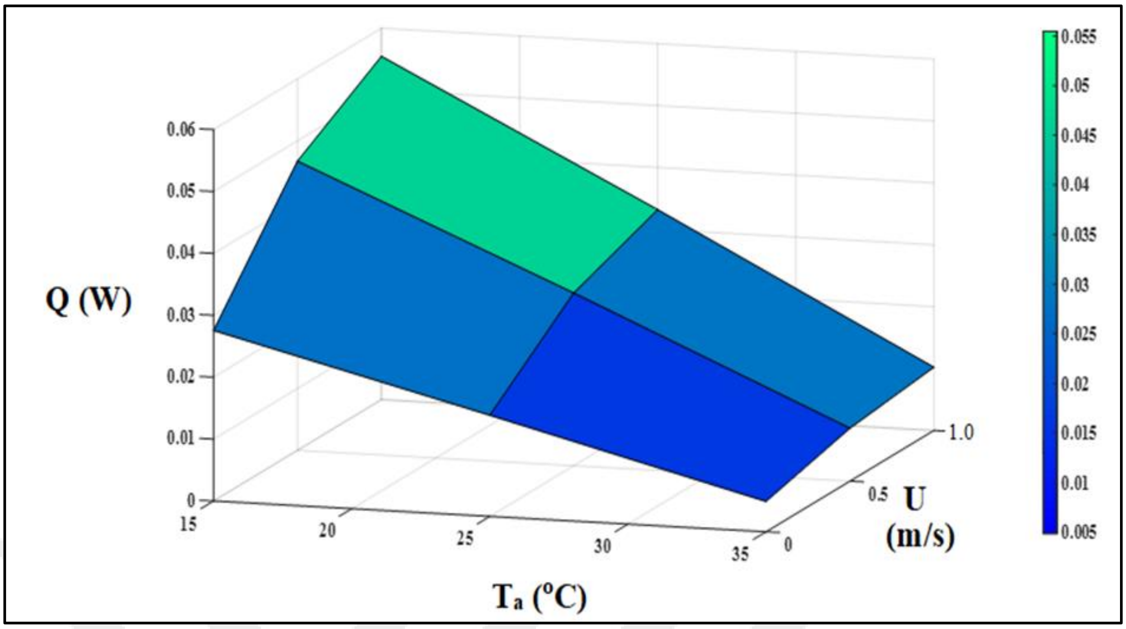

Figure A.4. Variation of the heat lost from the foraging honeybees with the air velocity and the atmospheric temperature under the sunshine when 0.5 M of sucrose is supplied at 15 μl/min of flow rate.

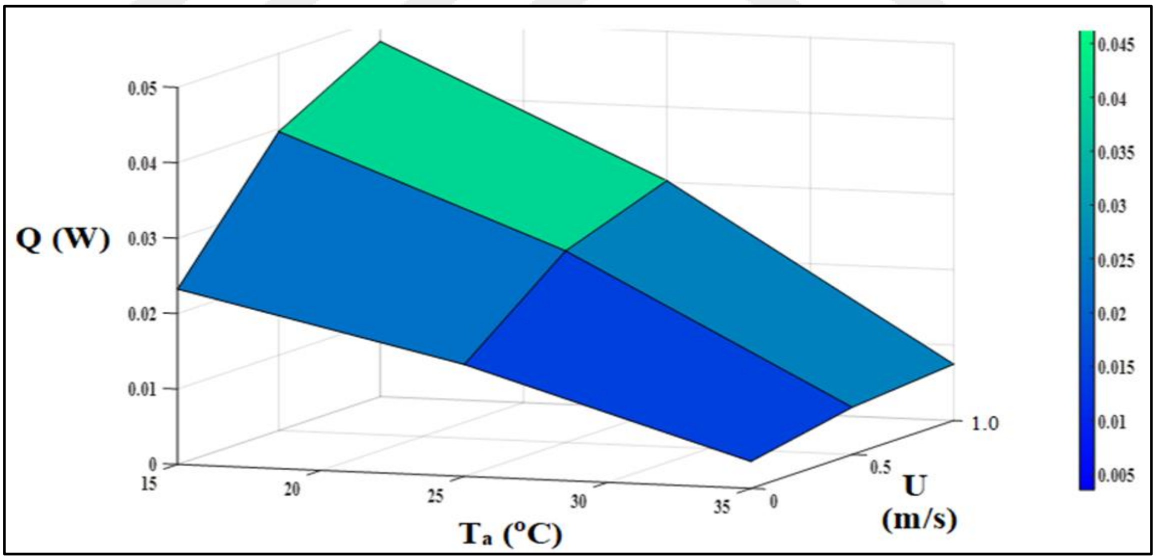

Figure A.5. Heat lost by the foraging honeybees depending on the air velocity and the atmospheric temperature at shade with 0.5 M of unlimited sucrose supply.

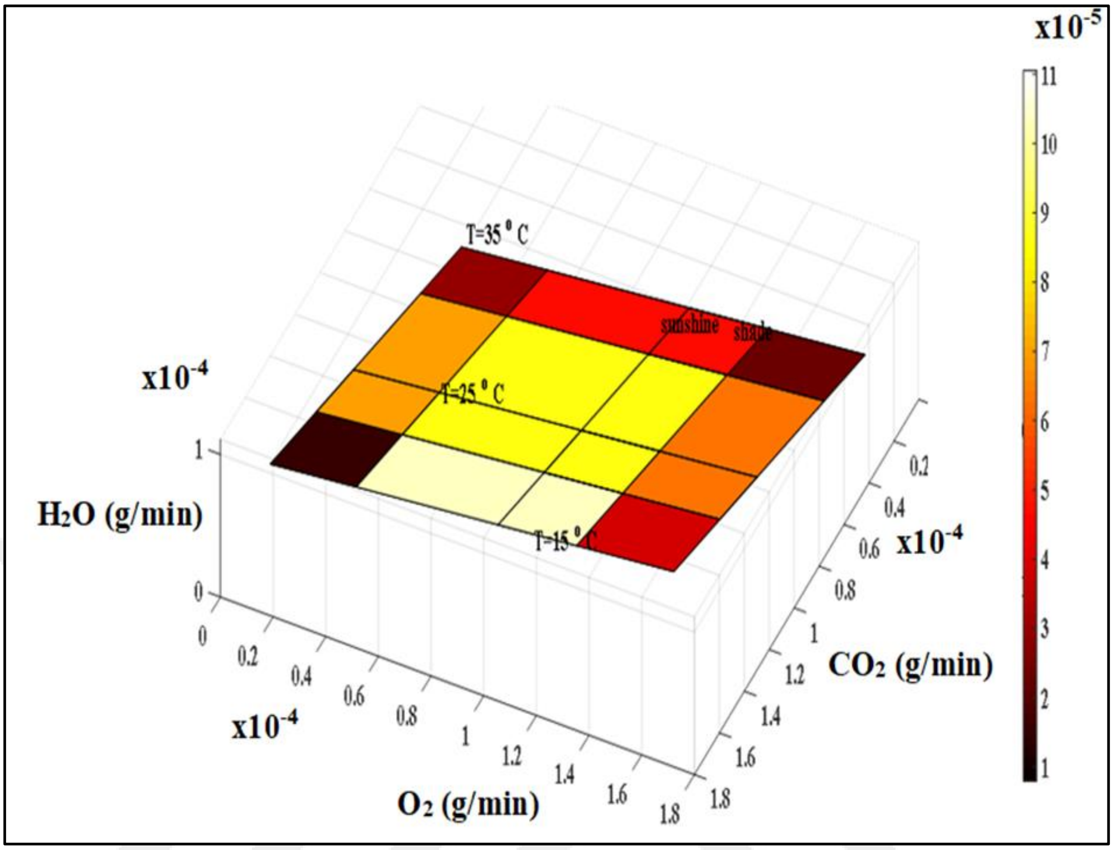

Figure A.6. Water uptake at 15, 25 and 35 °C by the foraging honeybees depending on the oxygen consumption and carbon dioxide production at shade and under the sunshine with 0.5 M of sucrose supply with 15 µl/min of flow rate.

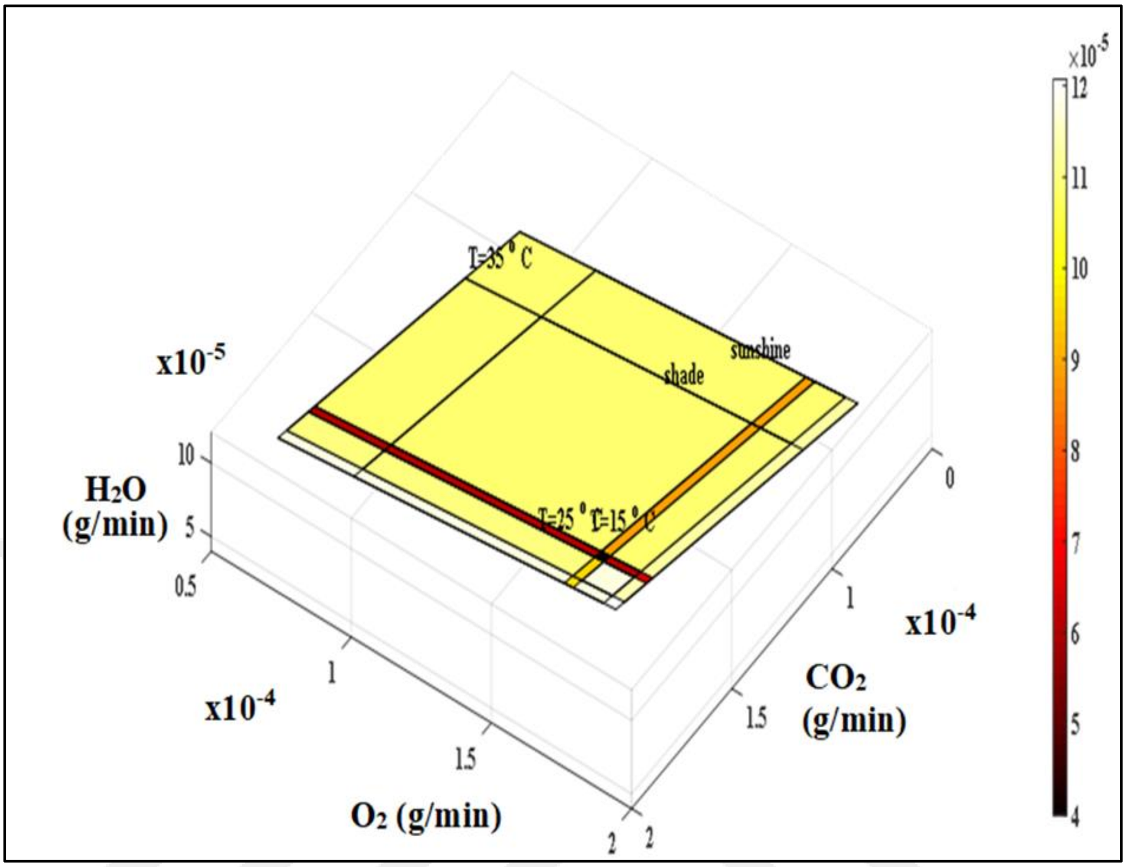

Figure A.7. Water uptake at 15, 25 and 35 °C by the foraging honeybees depending on the oxygen consumption and carbon dioxide production at shade and under the sunshine, with 0.5 M of unlimited sucrose supply.

APPENDIX B: MATLAB CODES FOR GRAPHS

Code1.The amount of heat up taken by foraging honey bee depending on air velocity and T_a under sun shine with 0.5 M of sucrose supply with 15 µl/min flow rate

```
clear
close all
per cent constants
A= 0.000016619; per cent surface area of thorax
D= 0.0023 ; per cent the sphere diameter
m= [1.802*10^-5 1.849*10^-5 1.895*10^-5] ; per cent dynamic viscosity of air
s= [1.225 1.184 1.145] ; per cent densitiy of air
v= [1.47*10^-5 1.562*10^-5 1.655*10^-5] ; per cent kinematik viscosity of air
cp= 1007 ; per cent specific heat capacity of air
k= [0.02476 0.02551 0.02625] ; per cent thermal conductivity of air
per cent data
Tth= [39.1 37.7 38.9] ; per cent thorax temperature
Pr= [0.7323 0.7296 0.7268] ;
hth= [41.3 38.9 35.1] ; per cent heat transfer coefficient for natural convection
Ta= [15,25,35] ; per cent ambient temperature
U= [0,0.5,1] ; per cent velocity of air affecting honeybee
[Ta,U] = meshgrid(Ta,U);
Q1=(Tth-Ta).*A.*((2+(((0.4.*(D.*s.*U./m).^0.5)+(0.06.*(D.*s.*U./m).^0.6666667)).*Pr.^0.4)).*k./D);
Q2= (Tth-Ta).*A.*hth ;
Qtoplam= Q1+Q2 ;
surf(Ta,U,Qtoplam); hold on
colormap winter
per cent xlabel('Ta (\circC)')
per cent ylabel('U (m/s)')
per cent zlabel('Q, heat up take (W)')
```

Code2.The amount of heat up taken by foraging honey bee depending on air velocity and T_a at shade with 0.5 M of sucrose supply with 15 µl/min flow rate

```
clear
close all
per cent constants
A= 0.000016619; per cent surface area of thorax
D=0.0023 ; per cent the sphere diameter
m= [1.802*10^-5 1.849*10^-5 1.895*10^-5] ; per cent dynamic viscosity of air
s= [1.225 1.184 1.145] ; per cent densitiy of air
k= [0.02476 0.02551 0.02625] ; per cent thermal conductivity of air
per cent data
Tth= [36.9 37.3 0] ; per cent thorax temperature
Pr= [0.7323 0.7296 0.7268] ;
hth= [40.8 38.7 0] ; per cent heat transfer coefficient for natural convection
Ta= [15,25,35] ; per cent ambient temperature
U= [0,0.5,1] ; per cent velocity of air affecting honeybee
[Ta,U] = meshgrid(Ta,U);
Q1=(Tth-Ta).*A.*((2+(((0.4.*(D.*s.*U./m).^0.5)+(0.06.*(D.*s.*U./m).^0.6666667)).*Pr.^0.4)).*k/D);
Q2= (Tth-Ta).*A.*hth ;
Qtoplam= Q1+Q2 ;
surf(Ta,U,Qtoplam); hold on
colormap winter
per cent xlabel('Ta (\circC)')
per cent ylabel('U (m/s)')
per cent zlabel('Q, heat up take (W)')
```

Code3.The amount of heat up taken by foraging honey bee depending on air velocity and T_a under sunshine, with 0.5 M of unlimited sucrose supply

```
clear
close all
per cent constants
A= 0.000016619; per cent surface area of thorax
D=0.0023 ; per cent the sphere diameter
m= [1.802*10^-5 1.849*10^-5 1.895*10^-5] ; per cent dynamic viscosity of air
s= [1.225 1.184 1.145] ; per cent densitiy of air
k= [0.02476 0.02551 0.02625] ; per cent thermal conductivity of air
per cent data
Tth= [41.1 40.8 40.0] ; per cent thorax temperature
Pr= [0.7323 0.7296 0.7268] ;
hth= [41.7 39.8 35.9] ; per cent heat transfer coefficient for natural convection
Ta= [15,25,35] ; per cent ambient temperature
U= [0,0.5,1] ; per cent velocity of air affecting honeybee
[Ta,U] = meshgrid(Ta,U);
Q1=(Tth-Ta).*A.*((2+(((0.4.*(D.*s.*U./m).^0.5)+(0.06.*(D.*s.*U./m).^0.6666667)).*Pr.^0.4)).*k/D);
Q2= (Tth-Ta).*A.*hth ;
Qtoplam= Q1+Q2 ;
surf(Ta,U,Qtoplam); hold on
colormap winter
per cent xlabel('Ta (\circC)')
per cent ylabel('U (m/s)')
per cent zlabel('Q, heat up take (W)')
```

Code4.The amount of heat up taken by foraging honey bee depending on air velocity and T_a at shade, with 0.5 M of unlimited sucrose supply

```
clear
close all
per cent constants
A= 0.000016619; per cent surface area of thorax
D=0.0023 ; per cent the sphere diameter
m= [1.802*10^-5 1.849*10^-5 1.895*10^-5] ; per cent dynamic viscosity of air
s= [1.225 1.184 1.145] ; per cent densitiy of air
v= [1.47*10^-5 1.562*10^-5 1.655*10^-5] ; per cent kinematik viscosity of air
cp= 1007 ; per cent specific heat capacity of air
k= [0.02476 0.02551 0.02625] ; per cent thermal conductivity of air
per cent data
Tth= [37.4 39.5 38.7] ; per cent thorax temperature
Pr= [0.7323 0.7296 0.7268] ;
hth= [40.9 39.4 35.2] ; per cent heat transfer coefficient for natural convection
Ta= [15,25,35] ; per cent ambient temperature
U= [0,0.5,1] ; per cent velocity of air affecting honeybee
[Ta,U] = meshgrid(Ta,U);
Q1=(Tth-
Ta).*A.*((2+(((0.4.*(D.*s.*U./m).^0.5)+(0.06.*(D.*s.*U./m).^0.6666667)).*Pr.^0.4)).*k./
D);
Q2= (Tth-Ta).*A.*hth ;
Qtoplam= Q1+Q2 ;
surf(Ta,U,Qtoplam); hold on
colormap winter
per cent xlabel('Ta (\circC)')
per cent ylabel('U (m/s)')
per cent zlabel('Q, heat up take (W)')
```

Code5.The amount of water up taken at15°C, 25°C and 35°C by foraging honey bee depending on oxygen consumption and carbon dioxide production at shade and under the sunshine , with 0.5 M of sucrose supply, with 15 µl/min flow rate

```
clear
close all
O2 = [1.7*10^-4 5.8*10^-5 1.5*10^-5 2.2*10^-4 1.2*10^-4];
CO2 = [2.4*10^-4 8.0*10^-5 2.1*10^-5 3.1*10^-4 1.7*10^-4];

per centconstant temperature
[X, Y] = meshgrid(O2,CO2);
for T=15:10:35
  H2O = 0.1998.*X + 0.4692.* Y; per cent comment rate of water intake
  surf(X,Y,H2O);
  colormap hot
end

xlabel('O2 (g/min)')
ylabel('CO2 (g/min)')
zlabel('H2O (g/min)')
text(1.5*10^-4,1.9*10^-4,  'T=15 ^o C');per cent insert text to the mesh
text(4.9*10^-5,1.0*10^-4, 'T=25 ^o C'); per cent insert text to the mesh
text(1.5*10^-5,0, 'T=35 ^o C');per cent insert text to the mesh
text(1.5*10^-4,4.9*10^-5,  'sunshine'); per cent insert text to the mesh
text(1.9*10^-4,1.0*10^-4,  'shade'); per cent insert text to the mesh
```

Code6.The amount of water up taken at 15°C, 25°C and 35°C by foraging honey bee depending on oxygen consumption and carbon dioxide production at shade and under the sunshine , with 0.5 M of unlimited sucrose supply.

```
clear
close all
O2 = [2.4*10^-4 2.1*10^-4 7.6*10^-5 2.2*10^-4 2.3*10^-4 1.1*10^-4];
CO2 = [3.4*10^-4 2.2*10^-4 1.40*10^-4 3.1*10^-4 3.2*10^-4 1.5*10^-4];

per cent constant temperature
[X, Y] = meshgrid(O2,CO2);
for T=15:10:35
  H2O = 0.1998.*X + 0.4692.* Y; per cent comment rate of water intake
  surf(X,Y,H2O);
  colormap hot
end

xlabel('O2 (g/min)')
ylabel('CO2 (g/min)')
zlabel('H2O (g/min)')
text(2.1*10^-4,1.88*10^-4,  'T=15 ^o C');per cent insert text to the mesh
text(1.5*10^-4,1.94*10^-4, 'T=25 ^o C'); per cent insert text to the mesh
text(6.4*10^-5,9.3*10^-5,    'T=35 ^o C');per cent insert text to the mesh
text(2.1*10^-4,1.5*10^-4,  'sunshine'); per cent insert text to the mesh
text(1.88*10^-4,1.94*10^-4,  'shade'); per cent insert text to the mesh
```

APPENDIX C: PSYCHROMETRIC CHART

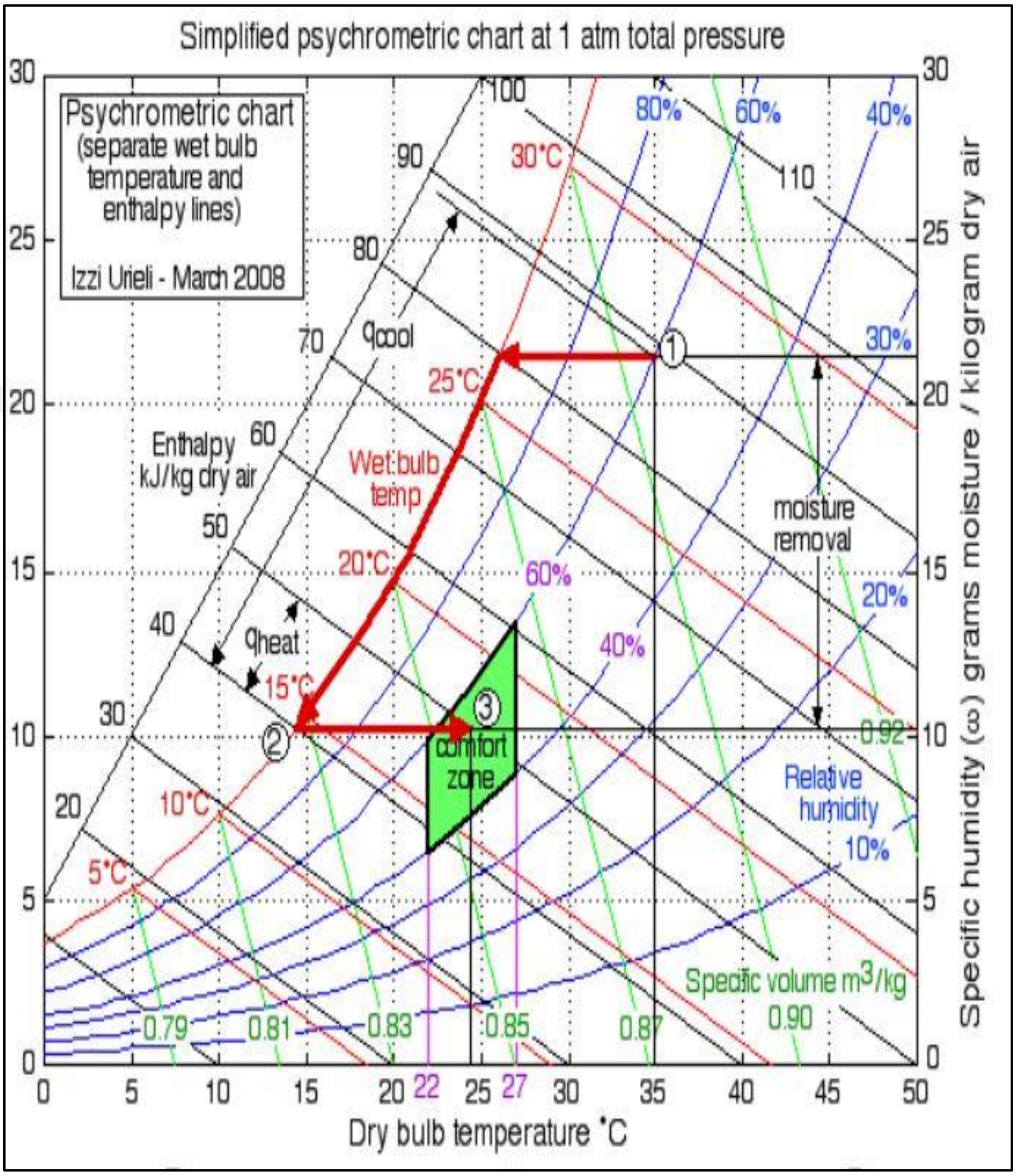

Figure C.1. The psychrometric chart of air [114]