

AN INVESTIGATION ON DIRECT FREE COOLING POTENTIAL OF CLIMATE  
IN KEY CITIES OF TURKEY

by

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*To my family and pets, who kept me in the warmth of love,*

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## **ABSTRACT**

### **AN INVESTIGATION ON DIRECT FREE COOLING POTENTIAL OF CLIMATE IN KEY CITIES OF TURKEY**

Data centers operating throughout the globe demanded up to 2% of world's electricity generation in the last decade, and they were responsible for the associated emissions and resources. There exists a potential of climate for times weather parameters comply with the environmental needs of our state of the art IT equipment, when the energy demand for cooling is offloaded to ambient air and both energy savings and reduction in emissions are realized, in so called Direct Free Cooling (DFC) mode of operation.

In this research, the direct free cooling potential of climate is investigated for the top socio-economically developed cities of Turkey, namely Istanbul, Ankara, and Izmir along with the city of Konya that is planned to almost double the data center whitespace area of Turkey, and Erzurum as the representative of a city with year-round cold ambient air temperatures and high elevation, in two different periods of time, a control period in the past and a subject period in future. The DFC potentials calculated for both periods of each city are compared within and between cities.

The findings reported in this research should affect policy and investment making processes due to changing climate. The aim is to establish sustainable and efficient data center operations in harmony with the climate of Turkey's key cities, leading to lesser green house gas emissions and more development.

## ÖZET

### **TÜRKİYE'NİN BELİRLİ İLLERİNDE İKLİMİN SERBEST SOĞUTMA POTANSİYELİ ÜZERİNE BİR ARAŞTIRMA**

Geçtiğimiz on yılda veri merkezleri dünyanın ürettiği elektrik enerjisinin yaklaşık yüzde ikisini kullandılar ve bu enerjinin üretiminde tüketilen kaynakların ve oluşan emisyonların sorumlusu oldular. Hava koşullarının çalıştırılan IT ekipmanının soğutma ihtiyaçlarıyla örtüştüğü zamanlarda kullanılabilen iklimin serbest soğutma potansiyeli, hem enerji ve kaynak tasarrufu yapılabilmesini hem de ilintili emisyonların azaltılabilmesini sağlamaktadır.

Bu çalışmada Türkiye'nin sosyo-ekonomik açıdan en gelişmiş illeri olan İstanbul, Ankara ve İzmir illeri ile kullanılabilir veri merkezi alanını yaklaşık iki katına çıkartacak yatırımlar yapılması beklenen Konya ve yıl boyunca soğuk bir iklim gözlemlenen, yüksek rakımlı Erzurum illerinde iklimin serbest soğutma potansiyeli geçmiş ve gelecekteki iki farklı periyod için araştırılmış ve serbest soğutma potansiyelleri iller içinde ve arasında her iki periyod için de karşılaştırılmıştır.

Bu araştırmada raporlanan bulguların değişen iklim çerçevesinde politika ve yatırım yapma süreçlerini etkilemesi beklenir. Amaç, Türkiye'nin belirli illerinde görülen iklime uyumlu, verimli ve sürdürülebilir veri merkezi işletmeleri tesis edilerek sera gazı emisyonlarının azaltılması ve kalkınmanın artırılmasıdır.

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## LIST OF SYMBOLS/ABBREVIATIONS

<b>Abbreviation</b>	<b>Explanation</b>
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
C	Celcius
CSCI	The Climate Savers Computing Initiative
DFC	Direct Free Cooling
DX	Direct Expansion
EPA	The U.S. Environmental Protection Agency
GCM	Global Circulation Model
GHG	Green House Gas
HVAC	Heating, Ventilating, and Air Conditioning
IaaS	Infrastructure as a Service
ICT	Information and Communications Technology
ICTP	The Abdus Salam International Centre for Theoretical Physics
IPCC	Intergovernmental Panel on Climate Change
IT	Information Technology
Kg	Kilogram
KUDAKA	Northeast Anatolia Development Agency
MPI-ESM-MR	Max Planck Institute for Meteorology Earth System Model MR
NRDC	The Natural Resources Defense Council
PaaS	Platform as a Service
RCP	Representative Concentration Pathways
RegCM	Regional Climate Model
SaaS	Software as a Service
S.d.	Standard Deviation
TC9.9	ASHRAE Technical Committee 9.9
TELKODER	Turkish Competitive Telco Operators Association
TIA-942	The Telecommunications Industry Association, ANSI/TIA-942-A Telecommunications Infrastructure Standard for Data Centers
UPS	Uninterruptible Power Supply

<b>Symbol</b>	<b>Explanation</b>	<b>Unit</b>
CH <sub>4</sub>	Methane	Kg
CO <sub>2</sub>	Carbon Dioxide	Kg
CO <sub>2</sub> eq	Carbon Dioxide Equivalent	Kg
CUE	Carbon Usage Effectiveness	Kg(CO <sub>2</sub> eq)/kWh
DBT	Dry Bulb Temperature	°C
DCE	Data Center Efficiency	
Dp	Dew Point	°C
PUE	Power Usage Efficiency	
RH	Relative Humidity	%

## 1. INTRODUCTION

“Data centers, the centralized facilities housing large number of IT equipment (e.g. servers, data storage, network devices, monitors, etc.) to perform various functions such as storage, management, processing and exchange of digital data and information, are essential support for the Information and Communication Technology” (Sun and Lee, 2006). These critical data center facilities also contain a significant investment of supporting systems and hardware, including air conditioning and climate control, fire suppression and smoke detection, secure entry and other specialized equipment for damage prevention and business continuity.

Technological developments that took place in the last decade caused an exponential increase in the size of data generated, processed, transferred and stored. Digitization of media and enhancements in resolutions of video and picture files that are not only consumed but also generated by an increasing number of mobile devices connected to internet gave rise to the adoption of cloud services provided to individuals by leading technology companies. Technology industry also offers Software as a Service (SaaS), Platform as a Service (PaaS) and Infrastructure as a Service (IaaS) to all business sectors trading off on-premise investments with reliance on cloud services and connectivity. All so-called cloud services, independent of their respective business models, are configured and run on proper IT infrastructures residing in data centers.

As business sectors and consumers shift towards more connected economies and lifestyles, respectively, the demand for computing, networking, and storage in the data center and across enterprise networks is expected to continue its growth, potentially resulting in an unsustainable increase in energy demand as well; thus the ICT industry must address energy consumption through increased energy efficiency (Climate Savers Computing Initiative, 2011). Adoption of energy efficiency measures with the shift towards cloud-based services have kept data center electricity demand in the United States (US) decoupled from the exponentially growing workloads for recent years, but the growth of energy demand by US data centers beyond 2020 is uncertain, as analysis of current trends indicate that the efficiency measures applied historically may not be enough for the data center workloads of the future (Shehabi, Smith, Masanet, and Koomey, 2018).

## **1.1. Energy Aspects of Data Centers**

On a global scale, electricity consumed by data centers in 2010 approximately accounted for between 1.1% and 1.5% of the world's total electricity generation. For US facilities that ratio was between 1.7 and 2.2% of the nation's annual electricity consumption, despite the fact that rapid rates of growth in data center electricity use that prevailed from 2000 to 2005 (EPA, 2007) had slowed significantly from 2005 to 2010 (Koomey, 2008 & 2011). US data centers' annual electricity consumption was an estimated 70 billion kilowatt-hours in 2014 and with a growth of 4% it is expected to reach 73 billion kilowatt-hours by 2020 (United States Data Center Energy Usage Report, 2016). Although 24% and 90% increases in energy demand were estimated in reference to 2005-2010 and 2000-2005 periods respectively, large hyper-scale data centers with high utilization rates caused by consolidation of the services on the cloud helped fulfilling the “improved operation scenario” projected in the EPA’s 2007 report to Congress.

In Turkey, commercial data center operators, banks, private sector and governmental organizations are estimated to own 12.000m<sup>2</sup>, 10.000m<sup>2</sup>, 25.000m<sup>2</sup> and 20.000m<sup>2</sup> of data center white space respectively, with an average power consumption of 1KWh per meter square of white space (TELKODER, 2015) where white space is defined as the total floor area that IT equipment can be placed for operation in the system room. Annual power consumption of data centers covered in Telkoder report yield approximately 587 million kilowatt-hours with data center utilization rates of 80% in Istanbul and 85% in Ankara by 2015. The total amount of data center white space is bound to grow in Turkey (Eymirli and Çiftçi (KUDAKA), 2016) and an additional 50.000m<sup>2</sup> of white space is projected to be built within Konya Ovası Project (KOP) alone, in accordance with KOP’s own Data Center Area research conducted in 2015. Assuming that data center investments continue, and average power consumption per squared meter of white space does not change, data centers in Turkey can potentially be consuming more than a billion kilowatt-hours of electricity annually in the near future.

### **1.1.1. Energy Consumption Breakdown of Data Centers**

In a data center, approximately half of the electricity supplied is accounted for the ICT equipment, and the other half is consumed by the supporting systems that are comprised of Uninterrupted Power Supply (UPS) units, illumination equipment, fans that move the air and cooling units. Figure 1.1. represents the average breakdown of energy usage by data centers;

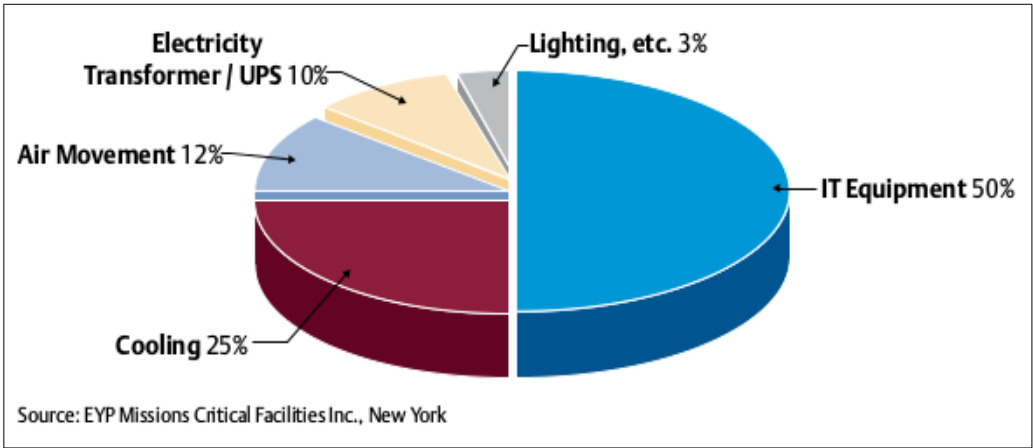


Figure 1.1. Average breakdown of energy end-use of a data center (EYP Missions Critical Facilities Inc., 2007).

Another case study of two data centers’ energy performance put forward their actual energy usage breakdown in figures 1.2. and 1.3. where power consumed by movement and conditioning of air are consolidated under the umbrella term Heating, Ventilating, and Air Conditioning (HVAC). This research indicates that 42% and 52% of total energy consumed by these two data centers were used to move, circulate and condition the air supplied to IT equipment racks in the data centers respectively. (Sun & Lee, 2006)

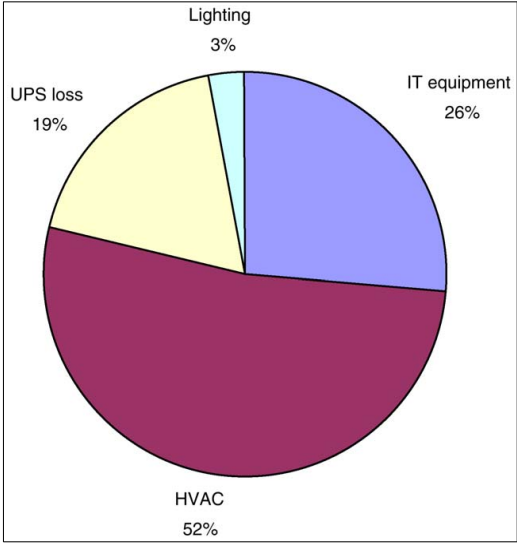
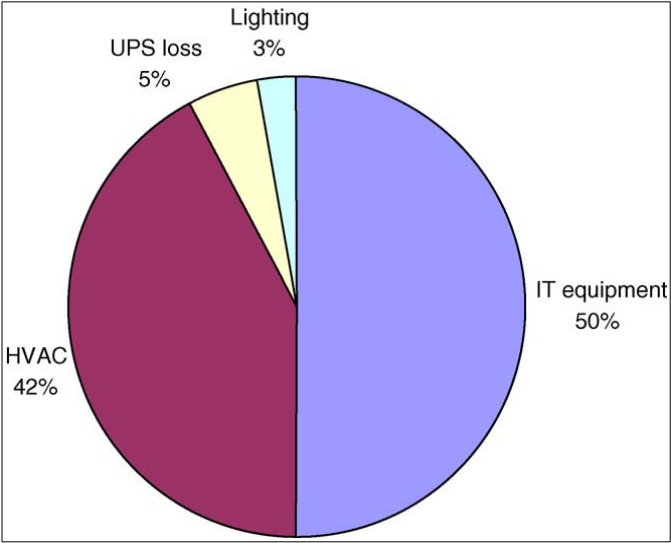


Figure 1.2. and 1.3. Breakdown of energy end-use by two data centers (Sun & Lee, 2006).

### 1.1.2. Energy Efficiency Metrics for Data Centers

The principal metric indicating the energy efficiency of a data center is the Power Usage Effectiveness (PUE) that was published in 2016 as a global standard under ISO/IEC 30134-2:2016. Power usage effectiveness is defined as the ratio of the total amount of energy used in a data center facility to the energy consumed by the IT equipment residing in that data center;

$$(Eq.1.) PUE = (\text{Total Facility Energy}) / (\text{IT Equipment Energy})$$

IT Equipment Energy includes total electric energy drawn by the computing, data storage and networking devices along with supplemental equipment, such as displays, annually.

Total Facility Energy delivered to the data center includes everything that supports the IT equipment such as power delivery components, air moving and cooling units, illumination and physical security equipment along with the energy consumed by the IT equipment itself annually.

PUE is a dimensionless metric that assumes values greater than 1;

$$[PUE] = [\text{kWh} / \text{year}] / [\text{kWh} / \text{year}]$$

Efficiency increase as PUE approaches to 1 from its greater values.

Reciprocal of PUE is another dimensionless metric called Data Center Efficiency (DCE);

$$(Eq.2.) DCE = 1 / (PUE) = (\text{IT Equipment Energy}) / (\text{Total Facility Energy})$$

$$[DCE] = [\text{kWh} / \text{year}] / [\text{kWh} / \text{year}]$$

These metrics provide a way to determine improvements in a data center's operational efficiency and to compare data centers' efficiencies between themselves.

Carbon Usage Effectiveness (CUE) is another metric pertaining to environmental protection and sustainability in the scope of data centers and is defined as follows;

$$(Eq.3.) CUE = (\text{Total CO}_2 \text{ Emissions due to Total Facility Energy}) / (\text{IT Equipment Energy})$$

The total CO<sub>2</sub> emissions value includes all Green House Gas (GHG) emissions, such as Carbon Dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>), in kilograms of carbon dioxide equivalent (kgCO<sub>2</sub>eq) summed over a year.

As IT Equipment Energy has units of kilowatt-hour per year (kWh/year), CUE metric is expressed in kilograms of carbon dioxide equivalent per kilowatt-hour;

$$[\text{CUE}] = [\text{kgCO}_2\text{eq} / \text{year}] / [\text{kWh} / \text{year}] = [\text{kgCO}_2\text{eq} / \text{kWh}]$$

Efficiency increases as total CO<sub>2</sub> emissions equivalent, hence CUE approaches to zero in value.

## **1.2. Cooling Paradigms of Data Centers**

The energy efficiency of most ICT equipment operational in data centers are of the order of 1%, implying that 99% of electric power consumed by the equipment is dissipated thermally, generating waste heat. Indoor climate management of data centers, built to contain numerous IT equipment characterized by low power efficiency and high heat dissipation while outdoor environmental conditions vary continuously is a challenging task since IT equipment requires strict adherence to environmental specifications during stages of operation and storage. Control over environmental parameters, namely dry bulb temperature, relative humidity and dew point, as defined by ASHRAE Technical Committee 9.9 and agreed upon by device vendors, is required. Therefore, data centers facilitate ventilation and cooling capacity adequate for the IT equipment contained as per TIA-942 standard, equating cooling requirement to heat generated, and heat generation to the electrical load of IT equipment, in turn claiming up to half a data center's annual energy consumption.

### **1.2.1. Cooling Requirements and Standards for the IT Equipment**

American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) is an international technical society organized to advance the arts and sciences of heating, ventilation, air-conditioning and refrigeration. ASHRAE Technical Committee 9.9 focuses on mission critical facilities, data centers and technology spaces that operate IT equipment and publishes the book "Thermal Guidelines for Data Processing Environments" by obtaining consensus from the major commercial IT equipment manufacturers for both "recommended" and "allowable" temperature and

humidity ranges and for six environmental classes, four of which apply to data centers. The third edition of Thermal Guidelines for Data Processing Environments book released in 2011 defines the environmental classes that apply to data centers as shown in Table 1.1.

Table 1.1. Definitions of data center environmental classes

<b>Environmental Class</b>	<b>Definition</b>
A1	Typically a data center with tightly controlled environmental parameters (dew point, temperature, and relative humidity) and mission critical operations; types of products typically designed for this environment are enterprise servers and storage products.
A2	Typically an information technology space or office or lab environment with some control of environmental parameters (dew point, temperature, and relative humidity); types of products typically designed for this environment are volume servers, storage products, personal computers, and workstations.
A3/A4	Typically an information technology space or office or lab environment with some control of environmental parameters (dew point, temperature, and relative humidity); types of products typically designed for this environment are volume servers, storage products, personal computers, and workstations.

In a data center, environmental parameters of dry bulb temperature, humidity and dew point are controlled for IT products in both operational and powered off states. ASHRAE Thermal Guidelines for Data Processing Environments define recommended and allowable environmental parameter ranges for both states of IT equipment. The recommended environmental parameters envelope define the limits under which IT equipment would operate the most reliably while still achieving reasonably energy-efficient data center operation, whereas allowable environmental parameters envelope define the absolute limits of these parameters, namely temperature, relative humidity and dew point, for the IT equipment. Operation outside the recommended but within the allowable envelope for short periods is not expected to have an effect on reliability or the operation of the IT equipment as per ASHRAE Thermal Guidelines. The environmental parameters that apply to classes A1, A2, A3 and A4 are given in table 1.2. (ASHRAE TC9.9, 2015)

Table 1.2. Thermal guidelines for data center environmental classes (ASHRAE, 2015)

Class <sup>a</sup>	Equipment Environmental Specifications for Air Cooling						
	Product Operations <sup>b,c</sup>					Product Power Off <sup>c,d</sup>	
	Dry-Bulb Temperature <sup>e,g</sup> °C	Humidity Range, Non-Condensing <sup>h,i,k,l</sup>	Maximum Dew Point <sup>k</sup> °C	Maximum Elevation <sup>e,j,m</sup> m	Maximum Temperature Change <sup>f</sup> in an Hour (°C)	Dry-Bulb Temperature °C	Relative Humidity <sup>k</sup> %
<b>Recommended</b> (Suitable for all 4 classes)							
A1 to A4	18 to 27	-9°C DP to 15°C DP and 60% RH					
<b>Allowable</b>							
A1	15 to 32	-12°C DP & 8% RH to 17°C DP and 80% RH <sup>k</sup>	17	3050	5 / 20	5 to 45	8 to 80
A2	10 to 35	-12°C DP & 8% RH to 21°C DP and 80% RH <sup>k</sup>	21	3050	5 / 20	5 to 45	8 to 80
A3	5 to 40	-12°C DP & 8% RH to 24°C DP and 85% RH <sup>k</sup>	24	3050	5 / 20	5 to 45	8 to 80
A4	5 to 45	-12°C DP & 8% RH to 24°C DP and 90% RH <sup>k</sup>	24	3050	5 / 20	5 to 45	8 to 80

(a) Classes A1 through A4 apply to data centers.

(b) Product equipment is powered on.

(c) Tape products require a stable and more restrictive environment. Typical requirements: minimum temperature is 15°C, maximum temperature is 32°C, minimum relative humidity is 20%, maximum relative humidity is 80%, maximum dew point is 22°C, rate of change of temperature is less than 5°C/h, rate of change of humidity is less than 5% RH per hour, and no condensation.

(d) Product equipment is removed from original shipping container and installed but not in use, e.g., during repair maintenance, or upgrade.

(e) A1 and A2 - Derate maximum allowable dry-bulb temperature 1°C/300 m above 950 m.

A3 - Derate maximum allowable dry-bulb temperature 1°C/175 m above 900 m.

A4 - Derate maximum allowable dry-bulb temperature 1°C/125 m above 900 m.

(f) For tape storage: 5°C in an hour. For all other ITE: 20°C in an hour and no more than 5°C in any 15 minute period of time.

(g) With diskette in the drive, the minimum temperature is 10°C (not applicable to Classes A1 or A2).

(h) The minimum humidity level for class A3 and A4 is the higher (more moisture) of the -12°C dew point and the 8% relative humidity.

These intersect at approximately 25°C. Below this intersection (~25°C) the dew point (-12°C) represents the minimum moisture level, while above it relative humidity (8%) is the minimum.

(i) Based on research funded by ASHRAE and performed at low RH, the following are the minimum requirements:

1) Data centers that have non-ESD floors and where people are allowed to wear non-ESD shoes may want to consider increasing humidity given that the risk of generating 8kV increases slightly from 0.27% at 25% RH to 0.43% at 8% RH (see Appendix D of reference [1] for more details).

2) All mobile furnishing/equipment is to be made of conductive or static dissipative materials and bonded to ground.

3) During maintenance on any hardware, a properly functioning and grounded wrist strap must be used by any personnel who contacts ITE.

(j) To accommodate rounding when converting between SI and I-P units, the maximum elevation is considered to have a variation of ±0.1%. The impact on ITE thermal performance within this variation range is negligible and enables the use of rounded values of 3050m (10,000ft).

(k) See Appendix L of ASHRAE TC9.9, Thermal Guidelines for Data Processing Environments, Fourth Edition, ASHRAE, Atlanta Georgia, 2015 for graphs that illustrate how the maximum and minimum dew-point limits restrict the stated relative humidity range for each of the classes for both product operations and product power off.

(l) For the upper moisture limit, the limit is the minimum absolute moisture of the DP and RH stated. For the lower moisture limit, the limit is the maximum absolute moisture of the DP and RH stated.

(m) Operation above 3050m requires consultation with IT supplier for each specific piece of equipment..

### **1.2.2. Data Center Cooling Concepts and Definition of DFC Potential**

In the current state of technology, air movement is the de facto method of discarding the waste heat generated within the IT equipment. Mechanical cooling of the air supplied to or recirculated in a data center is accomplished by HVAC systems that deploy either compressors exploiting direct expansion (DX) of refrigerant gases or water chilling systems that also make use of compressors and water pumps, albeit in a more energy-efficient way than DX systems. A data center can also deploy so-called air-side and water-side economizer units that exchange heat indirectly with the air and water bodies surrounding the facility, in order to offload mechanical cooling parts of the HVAC system and increase energy efficiency.

The concept of replacing the warm air generated inside a data center with filtered cold air supplied from immediate surroundings of the facility for the duration weather parameters satisfy the IT equipment's operating environmental envelopes defined in ASHRAE Thermal Guidelines is known as direct free cooling. Direct Free Cooling (DFC) mode of operation eliminates energy demand from mechanical cooling by completely offloading cooling function to ambient air. Therefore, air movement is the only contribution to facility power usage for cooling. The availability of direct free cooling for a data center in a particular geographic location is dictated by continuously varying temperature, relative humidity and dew point parameters of weather, and annual availability is expressed in terms of the total number of hours.

As the climate is the average state of the weather over a long period, one can define the direct free cooling potential of climate as the number of annual hours its relevant parameters satisfy the recommended environmental envelope for IT equipment classes A1 to A4 throughout a year of 8760 or 8784 hours.

### **1.2.3. Impact of Direct Free Cooling on Data Center Efficiency Metrics**

Since direct free cooling can significantly offload HVAC energy consumption, a constituent of Total Facility Energy, PUE and CUE metrics improve by approaching their respective ideal values of one and zero in this mode of operation. While an improvement in the PUE metric always implies that a facility is more energy-efficient, its CUE metric would not be affected in the extreme case where all facility power is supplied via renewable energy sources with zero carbon dioxide equivalent (CO<sub>2</sub>eq) emissions. Table 1.3. provides a breakdown of PUE to its components for different types of spaces housing IT equipment.

Table 1.3. PUE by data center component and space type (US D.C. Energy Usage Report, 2016)

Space Type	IT Eq.	Transformer	UPS	Cooling	Lighting	Total PUE
Server Closet	1	0.05	-	0.93	0.02	2
System Room	1	0.05	0.2	1.23	0.02	2.5
Localized D.C.	1	0.05	0.2	0.73	0.02	2
Midtier D.C.	1	0.05	0.2	0.63	0.02	1.9
High-end D.C.	1	0.03	0.1	0.55	0.02	1.7
Hyperscale D.C.	1	0.02	-	0.16	0.02	1.2

### 1.3. Objective of the Thesis

This study investigates the direct free cooling potential of climate for Istanbul, Ankara, Izmir, Konya, and Erzurum cities of Turkey between 2020 and 2049 years in comparison to the 1975-2004 period. Istanbul, Ankara and Izmir are selected as the most socio-economically developed cities of Turkey in order, according to SEGE-2011 research conducted by the Ministry of Development, whereas Konya is selected as the representative of Konya Ovası Projesi (KOP), which is of interest due to 50.000m<sup>2</sup> of potential data center white space foreseen by the KOP project and Erzurum represents a city with year-round cold ambient air temperatures and high elevation.

Hourly weather parameters from the most pessimistic future projection of climate for these cities are investigated for compliance with the recommended operating environmental envelope of IT equipment designated by ASHRAE in 2015. The annual sum of hours that ambient air parameters projected for a city satisfy both upper and lower bounds of the recommended envelope is proposed as the free cooling potential of the climate for a data center residing in the center of the city under investigation.

The aim of this study is to investigate the direct free cooling potential of climate and changes thereof, in Istanbul, Ankara, Izmir, Konya, and Erzurum cities of Turkey, by calculating and comparing this potential for 1975-2004 and 2020-2049 periods.

## 2. LITERATURE REVIEW

The first publicly available measurements on data center energy consumption were published by Mitchell-Jackson, Koomey, Nordman, and Blazek (Data center power requirements: measurements from Silicon Valley, 2003). Their research focused on overstatement of energy demands by data center operators, suggesting ten reasons behind exaggerated forecasts of time, including lack of common definitions and metrics, anticipation of high future loads and over-sized heating and ventilation and air conditioning (HVAC) systems. Authors benefited from exclusive access to a single data center located in Bay Area (California, U.S.) and used electricity billing data of four other data centers in their research, citing that “information on power use is a closely guarded proprietary secret for most data centers”. The measurements published indicate that approximately one half of the facility energy was used for IT equipment and HVAC energy requirements accounted for 38 percent. The research concludes that “standardized definitions and estimation methodologies can facilitate comparisons of data center energy use.”

Importance of data centers’ thermal management and energy-saving opportunities in suitable climates were put forward in the case study of a small data center facility in Sweden, by Fredrik Karlsson and Bahram Moshfegh (Investigation of indoor climate and power usage in a data center, 2005). The study revealed that 37% and 34% of the energy required in the data center facility were distributed to CRAC units and the central chiller plant respectively, surpassing IT equipment energy demand of 29%, including UPS losses. It was concluded in the research that power requirements could be reduced by making use of cold climate for passive cooling purposes, as in direct free cooling.

Research on patterns in practical energy use of data centers under tropical climatic conditions conducted by Sun and Lee (Case Study of Data Centers’ Energy Performance, 2006) revealed potential energy savings of 20% and 50% for the two data centers investigated. Subject facilities, both located in Singapore and operated by the government, had 97m<sup>2</sup> and 1048m<sup>2</sup> gross floor areas and 42% and 52% of their facility power were demanded by HVAC systems respectively. In order to compare energy use efficiency of these two data centers, Sun and Lee used a metric defined as the ratio of IT equipment energy consumption to the total data center energy consumption, the reciprocal of Power Usage Efficiency (PUE, Eq.1.) metric accepted as a global standard (ISO/IEC 30134-2:2016) in 2016, namely Data Center Efficiency (DCE, Eq.2.) metric. The research proposed that further characterization of data center facilities and global expansion of studies on energy use

patterns and potential improvements would result in establishment of a benchmarking database, along with best application practices and common design guidelines.

By 2007, the U.S. Environmental Protection Agency (EPA) developed a report on server and data center energy efficiency in response to the U.S. Congress' request stated in Public Law 109-431. Energy efficiency improvements for U.S. data centers were investigated under three alternative efficiency scenarios, namely improved operation, best practice, and state-of-the-art, and energy use trends associated with those scenarios were projected until the year 2011. It was shown that in the absence of any improvements in data center energy efficiency, historical and current efficiency trends surpassed 100 billion kWh annual consumption in five years starting from 2006. Therefore alternative efficiency scenarios assumed certain enhancements in IT equipment and site infrastructures, such as adoption of energy efficient IT equipment, consolidation of computing and storage systems, free cooling and direct liquid cooling. Enhancements assumed for each scenario are provided in Table 2.1. and associated electricity usage predictions are depicted in Figure 2.1. Further assumptions were that only 50% of current data centers would implement site infrastructure measures and the entire IT equipment stock would turn over within the five year long projection.

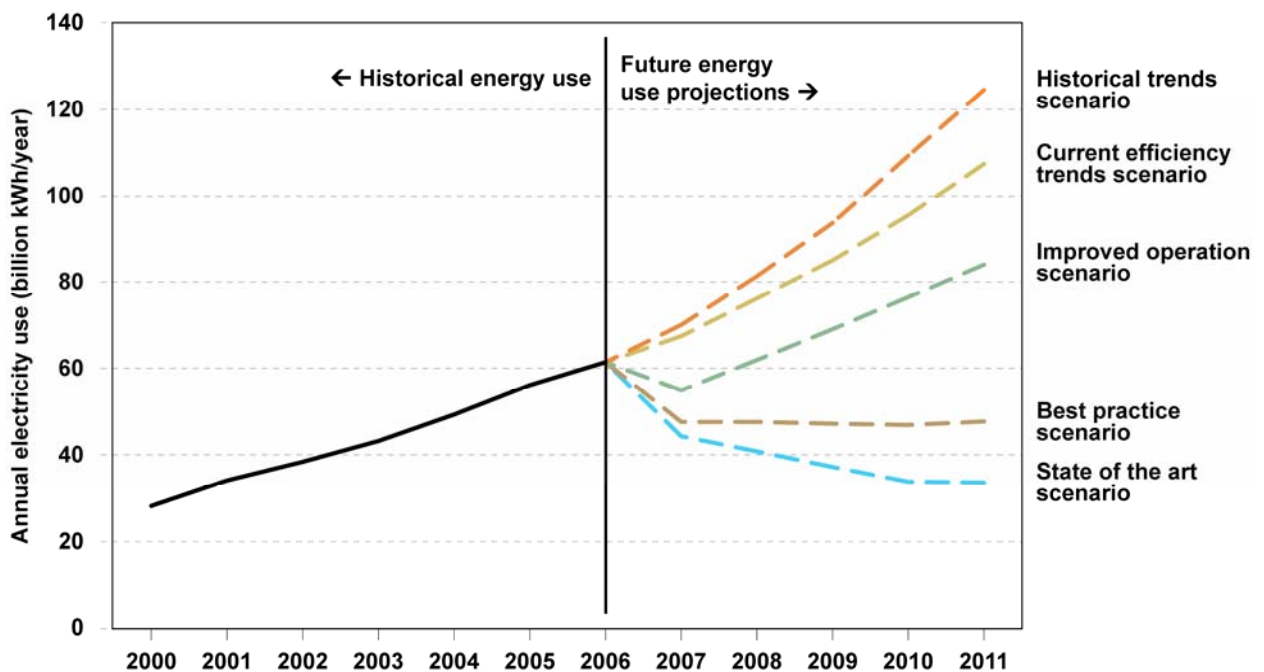


Figure 2.1. Comparison of projected electricity use, all scenarios, 2007 to 2011 (EPA, 2007)

Alternative efficiency scenarios predicted a total savings of 23 to 74 billion kWh electricity energy in five years time, resulting in a reduction of 15 to 47 million metric tons (MMT) in carbon dioxide (CO<sub>2</sub>) emissions by 2011.

Feasibility of free cooling, a site infrastructure improvement cited in the best practice scenario of EPA’s report, depends on two factors; IT equipment’s cooling requirements and availability of ambient air conforming to those requirements around the site throughout a year. A majority of IT equipment manufacturers had formed The Thermal Management Consortium for Data Centers and Telecommunications Rooms in 1998 with the purpose of addressing common problems in thermal management of data centers. In 2000, the consortium published the power density trend chart provided in Figure 2.2. in collaboration with the Uptime Institute, an American research and certification organization setting standards for data centers.

Table 2.1. Summary of assumptions for analysis of alternative efficiency scenarios (EPA, 2007)

Scenario	Data Center Subsystem	
	IT Equipment	Site Infrastructure (Power and Cooling)
Improved operation	Continue current trends for server consolidation:  Eliminate unused servers  Adopt “energy efficient” servers to modest level  Enable power management on 100% of applicable servers  Assume modest decline in energy use of enterprise storage equipment	30% improvement in infrastructure energy efficiency from improved airflow management
Best practice	All measures in “Improved operation” scenario, plus:  Consolidate servers to moderate extent  Aggressively adopt “energy-efficient” servers  Assume moderate storage consolidation	Up to 70% improvement in infrastructure energy efficiency from all measures in “Improved operation” scenario, plus:  Improved transformers and uninterruptible power supplies  Improved efficiency chillers, fans, and pumps  Free cooling
State-of-the-art	All measures in “Best practice” scenario, plus:  Aggressively consolidate servers  Aggressively consolidate storage  Enable power management at data center level of applications, servers, and equipment for networking and storage	Up to 80% improvement in infrastructure energy efficiency, due to all measures in “Best practice” scenario, plus:  Direct liquid cooling  Combined heat and power

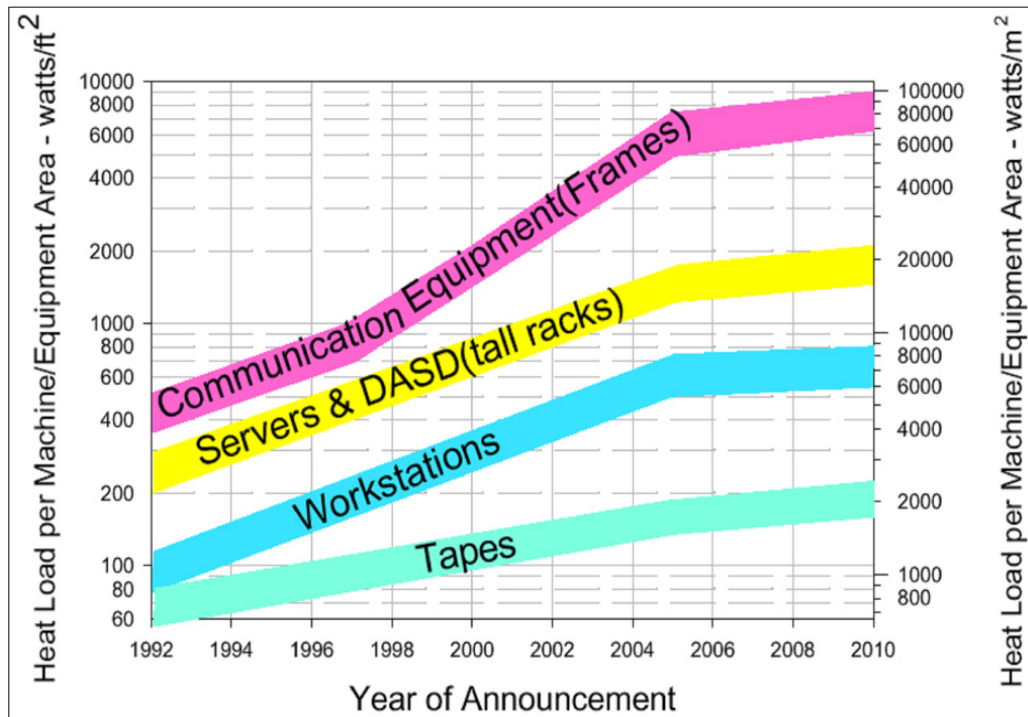


Figure 2.2. IT equipment power projection (Uptime Institute, 2000)

Following this publication showing increased power densities with time, three subgroups within the consortium were formed to address three problems industry was facing; Rack airflow requirements, accurate reporting of IT equipment heat loads and specification of common environmental conditions. Those subgroups' efforts to develop a set of guidelines led to formation of a new technical committee within the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE TC9.9) in 2002, with the aim of developing consensus documents that provide environmental trends and planning guidance for future data centers of the industry in relation to environmental issues. ASHRAE TC9.9 published the first version of "Thermal Guidelines for Data Processing Environments" in 2004 and released updated versions for 2008, 2011 and 2015 years, as provided in Appendix A. Side by side comparison of 2004 and 2008 versions of recommended environmental envelopes for the IT equipment, given in table 2.2., show that a colder low-end temperature, a warmer high-end temperature and a wider and better defined moisture range were adopted as the recommended threshold values of air delivered to the inlet of IT equipment. Expansion of the recommended environmental envelope improved the free cooling potential of many data center sites residing in diverse climates around the world.

Table 2.2. Comparison of 2004 and 2008 ASHRAE recommended operating envelopes

	<b>2004 Version</b>	<b>2008 Version</b>
Low End Temperature	20°C	18°C
High End Temperature	25°C	27°C
Low End Moisture	40% RH	5.5°C DP
High End Moisture	55% RH	60% RH & 15°C DP

The recommended environmental envelope published in 2011 did not differ from the 2008 version, however data center environmental classes A1, A2, A3 and A4 given in table 1.1. were introduced in this version along with their allowable environmental specifications, as guidelines were focused on informing the site operators as much as possible to allow them to make the best trade-off between IT equipment reliability and data center energy efficiency. The allowable environmental operating envelope, being wider than the recommended envelope leads to increased free cooling potential, therefore better energy efficiency for a site can be realized. However, continuous operation of IT equipment in this environmental envelope can also increase hardware power usage, acoustical noise and failure rates, therefore a trade-off between life expectancy and power efficiency is regarded. A psychrometric chart of ASHRAE 2011 environmental envelopes for data center environmental classes, and graphs showing server power trends and air flow rates versus ambient temperature are provided in Appendix B. A side-by-side comparison of 2011 and 2015 versions of ASHRAE recommended envelopes as in Table 2.3. reveal that a lower threshold for non-condensing humidity range was adopted for all environmental classes, further improving direct free cooling potential for sites in colder and moist climates.

Table 2.3. Comparison of 2011 and 2015 ASHRAE recommended operating envelopes

	<b>2011 Version</b>	<b>2015 Version</b>
Low End Temperature	18°C	18°C
High End Temperature	27°C	27°C
Low End Moisture	5.5°C DP	-9°C DP
High End Moisture	60% RH & 15°C DP	60% RH & 15°C DP

Following ASHRAE's updated 2011 environmental envelopes, The Green Grid, "a nonprofit industry consortium of end-users, policy-makers, technology providers, facility architects, and utility companies that has collaborated to improve the resource efficiency of data centers", released updated air-side free cooling maps for North America, Europe, and Japan in late 2011, depicting maximum geographic free cooling potential in average number of hours per year, based on last 10 years climate data and allowable operating envelopes of classes A2 and A3. These maps and the reference psychrometric chart are provided in Appendix C.

The efforts on setting new standards and updating existing ones with the aim of improving energy efficiency in data centers were based on continuous research and study on the field. Koomey, having contributed to EPA's report for congress, released a report on worldwide electricity used by data centers (Environmental Research Letters Vol.3, 2008), citing that the worldwide electric energy demanded by the data centers had doubled from 2000 to 2005 years due to growth in the number of volume servers deployed globally. In 2011, Koomey authored another report titled Growth In Data Center Electricity Use 2005 to 2010, showing that the growth in energy use of data centers over the 2005-2010 period was associated with the increase in electric power drawn by each server. Also, the U.S. data centers were consuming significantly lower than expected electric energy by 2010 due to overestimated number of installed servers by previous research.

The Climate Savers Computing Initiative, formed in 2007 as a nonprofit group of more than three hundred eco-conscious consumers, businesses and conservation organizations, aiming to reduce greenhouse gas emissions caused by computing and networking equipment, released two white papers referencing Koomey's 2011 research and EPA's 2007 Report to Congress, titled "Considerations for Selecting Power Supplies for Networking Equipment and Evaluating Power Conversion Efficiency", and "Energy Efficiency Guide for Networking Devices". The Climate Savers Computing Initiative merged with The Green Grid association in 2012 to accelerate the adoption and development of green computing.

The Natural Resources Defense Council (NRDC), an international nonprofit environmental organization with more than a million members and activists, released an analysis in 2012 under "Is Cloud Computing Always Greener? Finding the Most Energy and Carbon Efficient Information Technology Solutions for Small- and Medium-Sized Organizations" title, revealing that smaller server rooms and closets were responsible for about half of the electricity consumed by servers in U.S. while claiming that up to 40% reduction in electricity demanded by the servers deployed in U.S. could be realized. A follow-up analysis titled Data Center Efficiency Assessment (2014) by the same organization, cites deceleration of progress on energy efficiency and low utilization rates as the challenges and calls industry to take recommended actions.

In June 2016, Ernest Orlando Lawrence Berkeley National Laboratory released the United States Data Center Energy Usage Report that evaluates energy demanded by data centers of the U.S. starting from 2000 and projecting into 2020 by building on the 2007 EPA Report to Congress. The report attributes diminished increase in electricity consumption to three main factors; reduced growth in number of operational servers in data centers, electric power demand per server being an

invariant since 2005, and large hyper-scale data centers that host co-location servers and cloud services with PUE values close to 1.1. An annual electricity demand of 73 billion kWh was forecast for the U.S. data centers in year 2020.

Shehabi, Smith, Masanet and Koomey in their research, titled “Data Center Growth in the United States: Decoupling The Demand for Services from Electricity Use” (2018), provide U.S. data center electricity demand forecast until 2020 for three future scenarios; The current trends scenario couple historical and projected increases in number of deployed IT equipment and associated improvements in energy efficiency starting from 2000 to 2020, in contrast to alternative frozen efficiency scenario that keep energy efficiency at levels observed circa 2010 while increasing number of equipment deployed until 2020, and the best practices alternative that assume widespread adoption of the state of the art energy efficiency measures and the most energy-efficient IT equipment by all data centers as of 2020. The authors conclude that growth in energy consumption of data centers beyond 2020 is uncertain since historical improvements in energy efficiency might not be adequate for data center demands of the future. Projections of data center electricity use model in the research are provided in Figure 2.3.

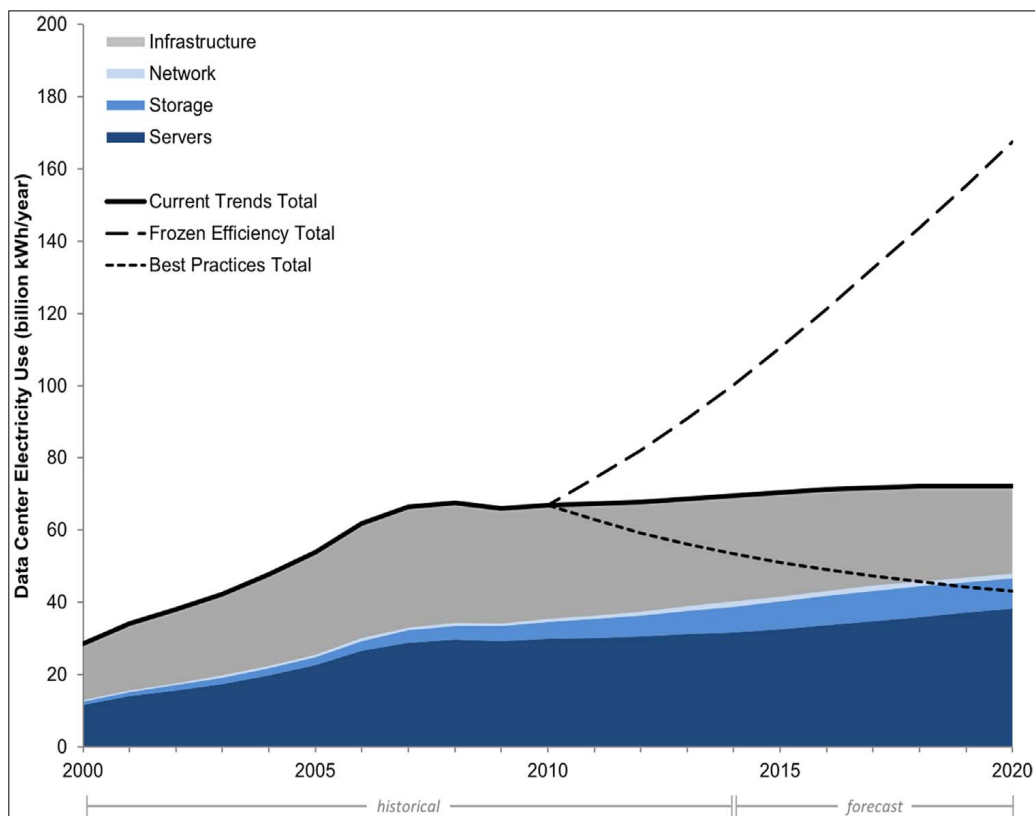


Figure 2.3. U.S. data center equipment electricity use trends from 2000 to 2020 (Shehabi, Smith, Masanet and Koomey, 2018)

### 3. METHODOLOGY

A hypothetical data center, capable of direct free cooling and hosting IT equipment diversified across four data center classes, is assumed to be operated in the center of the city under investigation, during periods from 2020 to 2049 and from 1975 to 2004. The number of hourly climate data points for the city center, projected by RegCM regional climate model, that satisfy both upper and lower thresholds of the recommended environmental envelope set by ASHRAE TC9.9 for IT equipment in operation is summed over as annual free cooling potential of climate.

#### 3.1. The Hypothetical Data Center

A hypothetical data center is assumed to be located in the city centers of Istanbul, Ankara, Izmir, Konya, and Erzurum. The geographical data used in this research are provided in Table 3.1.

Table 3.1. Geographical city center coordinates

	Decimal Degrees (DD)	Degrees/Minutes/Seconds (DMS)	Altitude (mt.)
<b>Istanbul</b>	41.01384 , 28.94966	41°00'49.82" N , 28°56'58.78" E	39
<b>Ankara</b>	39.91987 , 32.85427	39°55'11.53" N , 32°51'15.37" E	874
<b>Izmir</b>	38.41273 , 27.13838	38°24'45.83" N , 27°08'18.17" E	122
<b>Konya</b>	37.87135 , 32.48464	37°52'16.86" N , 32°29'04.70" E	1030
<b>Erzurum</b>	39.90861 , 41.27694	39°54'31.00" N , 41°16'36.98" E	1914

The maximum allowable temperature specification of IT equipment derates by 1°C for every 300 metres above 950 metres for classes A1 and A2 and 1°C per each 175 metres and 125 metres above 900 metres for classes A3 and A4 respectively, as per footnote (d) of 2015 ASHRAE Thermal Guidelines for Data Center Environmental Classes (Table 1.2.). Derated maximum allowable temperature thresholds for Konya and Erzurum, given in Table 3.2., are found to be higher than, thus not interfering with, the maximum temperature limit (27°C) of the recommended operating envelope.

Table 3.2. Altitude adjusted maximum allowable temperatures (°C) in product operation

	Environmental Class			
	A1	A2	A3	A4
<b>Konya</b>	31°C	34°C	39°C	43°C
<b>Erzurum</b>	28°C	31°C	34°C	36°C

Two different cooling modes are available for the hypothetical data center; In direct free cooling mode, filtered ambient air is directly supplied to data center white space during hours that temperature and humidity parameters of the weather satisfy the recommended environmental envelope (Table 1.2. , Table 2.3.). Operation in mechanical cooling mode is assumed for all other hours with non-compliant weather parameters.

The annual number of hours direct free cooling would be available for a data center located in each city is calculated as the direct free cooling potential of climate for the periods from 2020 to 2049 and from 1975 to 2004.

### **3.2. Climate Data**

Future projections of local climate are achieved by running a low resolution global circulation model (GCM) under a certain Representative Concentration Pathways (RCP) (Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J. F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J., Rose, S. K., 2011) scenario and by using the output of GCM as the initial and boundary conditions of a regional climate model that can produce higher-resolution output.

MPI-ESM-MR global circulation model, originally developed by The Max Planck Institute for Meteorology (MPI-M), is run with the RCP8.5 scenario. Predicting CO<sub>2</sub> emissions of 936 ppm in the atmosphere by the end of the century, RCP8.5 is the business as usual scenario representing the worst case of greenhouse gas emissions among other RCP scenarios adopted by the Intergovernmental Panel on Climate Change (IPCC). Horizontal grid resolution of data generated by MPI-ESM-MR model is approximately 139 kilometers, this resolution is increased to 50 kilometers by the first run of the regional climate model, RegCM version 4.4, developed by The Abdus Salam International Centre for Theoretical Physics (ICTP) (Pal, J. S., Giorgi, F., Bi, X., Elguindi, N., Solmon, F., Rauscher, S. A., Gao, X., Francisco, R., Zakey, A., Winter, J., Ashfaq, M., Syed, F. S., Sloan, L. C., Bell, J. L., Diffenbaugh, N. S., Karmacharya, J., Konaré, A., Martinez, D., Da Rocha, R. P., Steiner, A. L., 2007). RegCM is run for a second time with the output of the initial run, in order to produce a data set with a horizontal resolution of 10 kilometers. Regional climate model parameterization and validity checks are as accomplished by Turp, M. T., Öztürk, T., Türkeş, M., and Kurnaz, M. L., 2014.

The climate parameters projected with 10 km horizontal resolution are interpolated as the distance-weighted average of four grid points that are the nearest neighbours of city center coordinates provided in Table 3.1. Hourly climate dataset for this point is generated by linear interpolation of data points projected in three-hour timesteps. The dew point temperature is derived from the projected temperature and relative humidity values for all data points, using The Magnus formula (Sonntag D., 1990) with parameters that are valid within the -45°C to 60°C range, as supplied in Appendix D.

Two different data sets, covering 1975 to 2004 and 2020 to 2049 periods, are generated as control and subject for each city. Each data set contains 262992 rows of hourly weather information consisting of date, time, dry bulb temperature, dew point temperature, and relative humidity parameters, as organized and sampled in Table 3.3.

Table 3.3. A sample data set with three data points

Date	Time	Dry Bulb Temperature (°C)	Dew Point Temperature (°C)	Relative Humidity (%)
2039-09-03	09:00:00	20.2556	16.6823	79.9544
2039-09-03	10:00:00	20.6935	16.9545	79.1796
2039-09-03	11:00:00	21.1314	17.2244	78.4049

### 3.3. Analysis of Climate Data

Each climate parameter valid for the date and time indicated is tested for compliance with recommended environmental parameter thresholds defined in the 2015 ASHRAE Thermal Guidelines for Data Center Environmental Classes (Table 3.4.).

Table 3.4. 2015 ASHRAE recommended operating envelope

Low End Temperature	18°C
High End Temperature	27°C
Low End Moisture	-9°C DP
High End Moisture	60% RH & 15°C DP

If, for a given data point, the temperature is between 18°C to 27°C, and the dew point is between -9°C and 15°C, and relative humidity is at or below 60%, that particular data point contributes an hour to the direct free cooling potential of climate for the date and time it belongs. Table 3.5. shows an analysis of weather parameters from select data points for direct free cooling eligibility.

Table 3.5. Analysis of select data points

Date	Time	$18^{\circ}\text{C} \leq \text{DBT} \leq 27^{\circ}\text{C}$	$-9^{\circ}\text{C} \leq \text{DP} \leq 15^{\circ}\text{C}$	$\text{RH} \leq 60\%$	DFC ?
1983-08-04	10:00:00	18.04	12.02	<b>67.88</b>	F
1998-09-04	11:00:00	25.24	<b>15.96</b>	56.43	F
2002-08-09	23:00:00	<b>12.25</b>	1.68	48.46	F
2024-04-21	11:00:00	<b>18.46</b>	9.78	56.99	T
2024-05-19	17:00:00	22.42	13.70	57.82	T
2039-09-03	09:00:00	20.26	<b>16.68</b>	<b>79.95</b>	F

Values in bold are out of range.

T : True , F : False

The total number of hourly data points that direct free cooling mode could be deployed in a hypothetical data center is calculated as yearly bins and sum of time series, covering 1975 to 2004 and 2020 to 2049 periods as control and subject data sets of the city under investigation respectively. Calculated mean, standard deviation and extreme values of both data sets, reported in numeric values and percentiles are compared within a city to present effects of changing climate, and between cities direct free cooling potentials are compared.

## **4. RESULTS and DISCUSSION**

This research reveals the minimum direct free cooling potential of climate for the cities analyzed, by restricting weather parameters to the recommended environmental envelope of ASHRAE's 2015 Thermal Guidelines, and the resolution is one hours. The DFC potentials calculated are compared between control and subject periods for individual cities and a comparative analysis of DFC potentials between cities for both periods complete with standard deviations are also provided and depicted with column charts. Non mutually exclusive parameters of climate data are analyzed for trends due to climate change. This section is concluded with the discussion on implications of investigation of direct free cooling potential.

### **4.1. Direct Free Cooling Potential of Individual City Climates**

DFC potential calculated for control and subject climate data sets, as the sum of eligible hours in time series, are reported for each city, in tabulated form that show extreme values in bold. The potential is also presented with column charts that highlight the extreme and the mean values. The numerical analysis of DFC potentials for [1975,2004] and [2020,2049] periods are provided and significant changes observed between these periods are summarized for subject cities.

#### 4.1.1. Istanbul

Table 4.1. Yearly DFC potential of climate in Istanbul by hours

Year [1975,2004]	Annual DFC Hours		Year [2020,2049]	Annual DFC Hours
1975	614		2020	456
1976	382		2021	481
1977	474		2022	541
1978	629		2023	418
1979	403		2024	308
1980	448		2025	311
1981	397		2026	531
1982	760		2027	425
1983	551		2028	217
1984	288		2029	378
<b>1985</b>	<b>776</b>		2030	383
1986	526		2031	254
1987	585		2032	313
1988	418		2033	241
1989	364		2034	617
1990	341		2035	332
1991	615		2036	275
1992	619		2037	385
1993	204		2038	235
1994	553		2039	375
1995	455		2040	562
<b>1996</b>	<b>166</b>		2041	464
1997	258		2042	530
1998	663		2043	208
1999	690		2044	433
2000	433		2045	452
2001	745		2046	400
2002	432		2047	386
2003	249		<b>2048</b>	<b>158</b>
2004	373		<b>2049</b>	<b>624</b>

Table 4.2. Numerical analysis of DFC potential of climate in Istanbul by hours

Istanbul	Total DFC Potential	Mean DFC Potential	Standard Deviation	Lowest DFC Potential	Highest DFC Potential
[1975,2004]	14411	480.37	166.71	166	776
[2020,2049]	11693	389.77	123.40	158	624
$\Delta$ Difference	-2718	-90.60	-43.31	-8	-152

Table 4.3. Numerical analysis of DFC potential of climate in Istanbul by percentile

Istanbul	Mean DFC Potential	Relative SD	Lowest DFC Potential	Highest DFC Potential
[1975,2004]	5.48%	34.71%	1.89%	8.85%
[2020,2049]	4.45%	31.66%	1.80%	7.12%
$\Delta$ Difference	-1.03%	-3.05%	-0.09%	-1.73%

During [2020,2049] period, the climate in Istanbul will be able to support direct free cooling for 4.45% of the time on the average, which is a decrease of 90.6 hours in mean DFC potential from the control period. A change of -3.05% in relative standard deviation implies fewer fluctuations are expected to occur in year-over-year DFC potentials of Istanbul with respect to the control period, yet deviations are approximately 1/3 of the mean DFC potential. The minimum DFC potential of 158 hours and a maximum of 624 hours are observed to occur in consecutive years of 2048 and 2049.

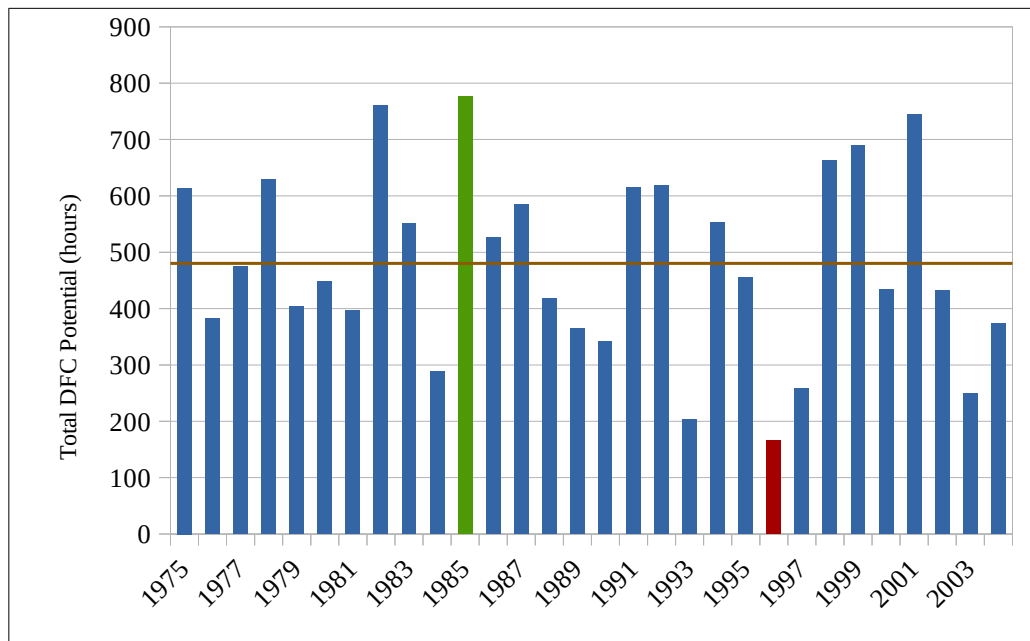


Figure 4.1. Annual number of DFC hours observed during control period of Istanbul

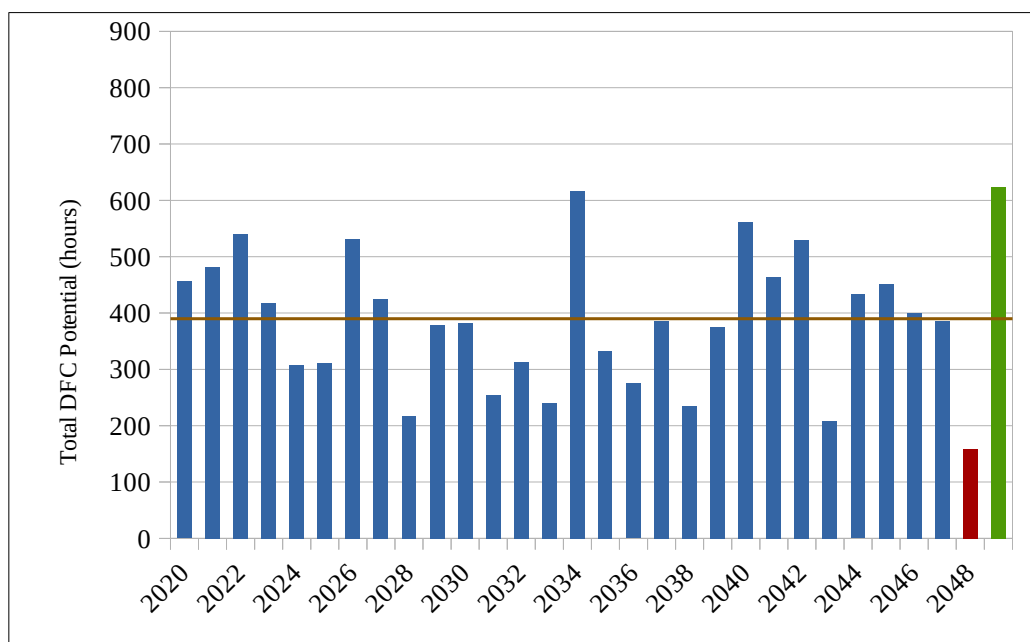


Figure 4.2. Annual number of DFC hours observed during subject period of Istanbul

#### 4.1.2. Ankara

Table 4.4. Yearly DFC potential of climate in Ankara by hours

Year [1975,2004]	Annual DFC Hours		Year [2020,2049]	Annual DFC Hours
1975	1196		2020	1354
1976	1263		2021	1290
1977	1184		2022	1251
1978	1276		2023	1333
1979	993		2024	1135
1980	1067		2025	1300
1981	1222		2026	1368
1982	1360		2027	1332
1983	1137		2028	1136
1984	1203		2029	1104
1985	1358		2030	1255
1986	1073		2031	1194
1987	1303		2032	1359
1988	1305		<b>2033</b>	<b>987</b>
1989	1042		2034	1318
1990	1171		2035	1232
1991	1233		2036	1280
1992	1405		2037	1092
<b>1993</b>	<b>966</b>		2038	1201
1994	1203		2039	1339
1995	1120		2040	1352
1996	1015		2041	1346
1997	1188		2042	1376
1998	1321		2043	1211
<b>1999</b>	<b>1511</b>		2044	1181
2000	1132		2045	1291
2001	1480		2046	1468
2002	1307		2047	1354
2003	1144		2048	1427
2004	1240		<b>2049</b>	<b>1570</b>

Table 4.5. Numerical analysis of DFC potential of climate in Ankara by hours

Ankara	Total DFC Potential	Mean DFC Potential	Standard Deviation	Lowest DFC Potential	Highest DFC Potential
[1975,2004]	36418	1213.93	135.51	966	1511
[2020,2049]	38436	1281.20	120.58	987	1570
$\Delta$ Difference	2018	67.27	-14.93	21	59

Table 4.6. Numerical analysis of DFC potential of climate in Ankara by percentile

Ankara	Mean DFC Potential	Relative SD	Lowest DFC Potential	Highest DFC Potential
[1975,2004]	13.85%	11.16%	11.02%	17.24%
[2020,2049]	14.61%	9.41%	11.26%	17.91%
$\Delta$ Difference	0.77%	-1.75%	0.24%	0.67%

For the [2020,2049] period, Ankara climate will be able to support direct free cooling for 14.61% of the time on the average, which is a slight increase of 67.27 hours in mean DFC potential from the control period. A change of -1.75% in relative standard deviation implies fewer fluctuations are expected to occur in year-over-year DFC potentials of Ankara with respect to the control period and deviations are approximately 1/10 of the mean DFC potential. The minimum DFC potential of 987 hours and a maximum of 1570 hours are observed to occur in years 2033 and 2049 respectively.

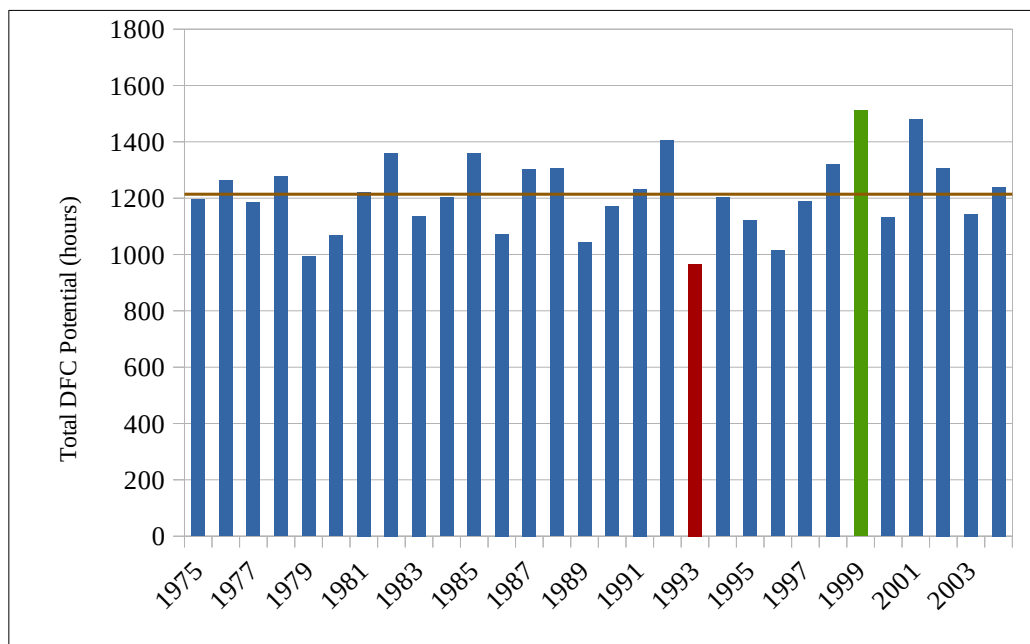


Figure 4.3. Annual number of DFC hours observed during control period of Ankara

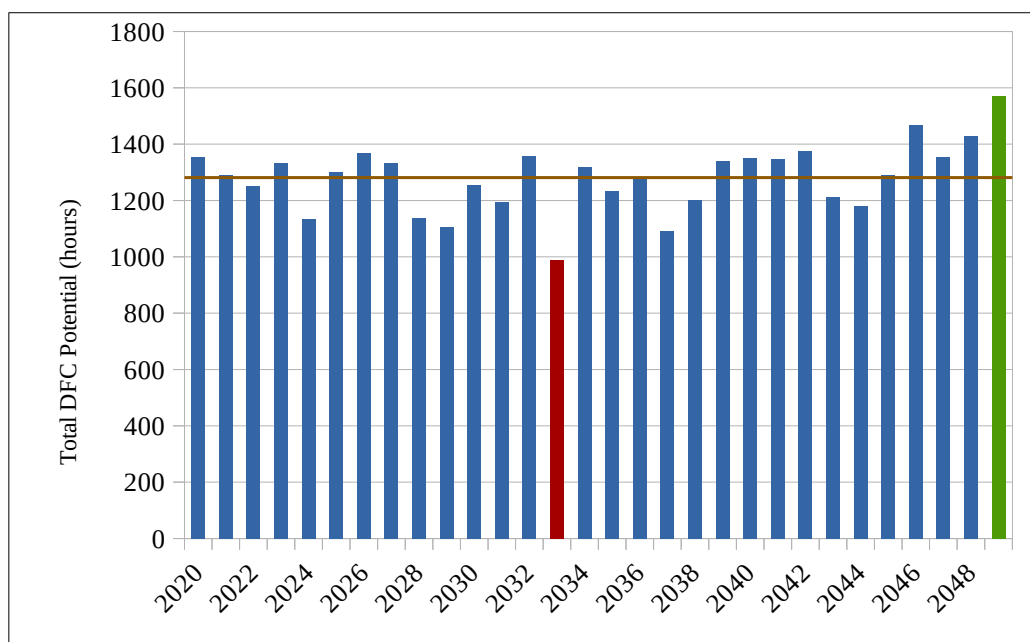


Figure 4.4. Annual number of DFC hours observed during subject period of Ankara

### 4.1.3. Izmir

Table 4.7. Yearly DFC potential of climate in Izmir by hours

Year [1975,2004]	Annual DFC Hours	Year [2020,2049]	Annual DFC Hours
1975	1366	2020	1486
1976	1238	2021	1352
1977	1327	2022	1424
1978	1544	2023	1158
1979	1108	2024	1075
1980	980	2025	1105
1981	1317	2026	1456
<b>1982</b>	<b>1875</b>	2027	932
1983	1557	2028	1017
1984	1128	2029	1473
1985	1570	2030	1090
1986	1130	2031	1104
1987	1200	2032	1262
1988	1077	2033	1228
1989	1376	2034	1325
1990	1243	2035	1379
1991	1507	2036	928
1992	1663	2037	1104
1993	973	2038	756
1994	1310	2039	1194
1995	1194	<b>2040</b>	<b>1564</b>
<b>1996</b>	<b>768</b>	2041	1079
1997	1154	2042	1288
1998	1321	<b>2043</b>	<b>729</b>
1999	1742	2044	1293
2000	1128	2045	1433
2001	1484	2046	1149
2002	1311	2047	1115
2003	1040	2048	990
2004	1083	2049	1335

Table 4.8. Numerical analysis of DFC potential of climate in Izmir by hours

Izmir	Total DFC Potential	Mean DFC Potential	Standard Deviation	Lowest DFC Potential	Highest DFC Potential
[1975,2004]	38714	1290.47	247.29	768	1875
[2020,2049]	35823	1194.10	211.04	729	1564
$\Delta$ Difference	-2891	-96.37	-36.25	-39	-311

Table 4.9. Numerical analysis of DFC potential of climate in Izmir by percentile

Izmir	Mean DFC Potential	Relative SD	Lowest DFC Potential	Highest DFC Potential
[1975,2004]	14.72%	19.16%	8.76%	21.39%
[2020,2049]	13.62%	17.67%	8.32%	17.84%
$\Delta$ Difference	-1.10%	-1.49%	-0.44%	-3.55%

During the [2020,2049] period, the climate in Izmir will be able to support direct free cooling for 13.62% of the time on the average, which is a decrease of 96.37 hours in mean DFC potential from the control period. The -1.49% change in relative standard deviation implies fewer fluctuations are expected to occur in year-over-year DFC potentials of Izmir with respect to the control period and approximately 1/6 of the mean DFC potential. The minimum DFC potential of 729 hours and a maximum of 1564 hours are observed to occur in years 2043 and 2040 respectively.

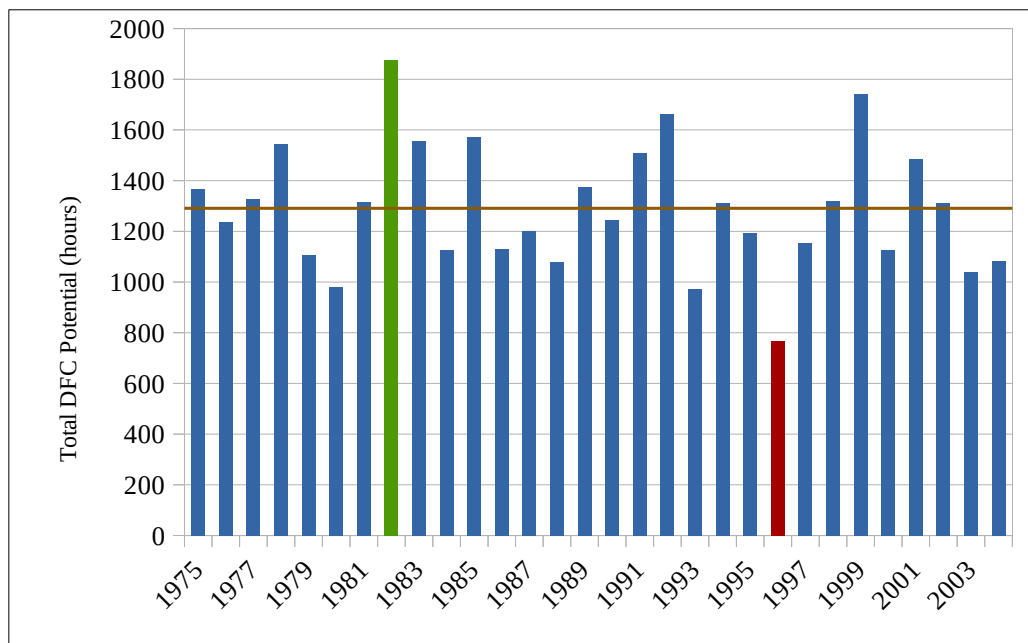


Figure 4.5. Annual number of DFC hours observed during control period of Izmir

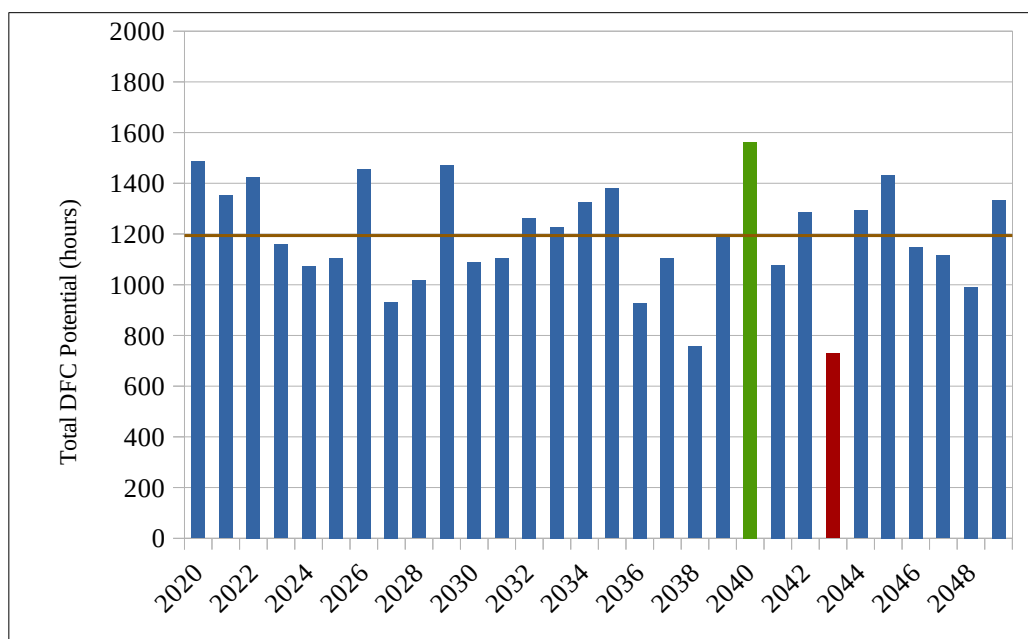


Figure 4.6. Annual number of DFC hours observed during subject period of Izmir

#### 4.1.4. Konya

Table 4.10. Yearly DFC potential of climate in Konya by hours

Year [1975,2004]	Annual DFC Hours		Year [2020,2049]	Annual DFC Hours
1975	1454		2020	1502
1976	1582		2021	1559
1977	1479		2022	1560
1978	1489		2023	1572
1979	1186		2024	1450
1980	1290		2025	1685
1981	1447		2026	1600
1982	1622		2027	1650
1983	1369		2028	1476
1984	1540		2029	1327
1985	1541		2030	1383
1986	1455		2031	1528
1987	1448		2032	1548
1988	1491		2033	1413
1989	1398		2034	1657
1990	1390		2035	1511
1991	1384		2036	1533
1992	1586		<b>2037</b>	<b>1315</b>
1993	1297		2038	1523
1994	1308		2039	1616
1995	1350		2040	1601
<b>1996</b>	<b>1159</b>		2041	1587
1997	1408		2042	1668
1998	1621		2043	1581
1999	1734		2044	1399
2000	1387		2045	1570
<b>2001</b>	<b>1746</b>		2046	1653
2002	1475		2047	1608
2003	1447		2048	1761
2004	1617		<b>2049</b>	<b>1929</b>

Table 4.11. Numerical analysis of DFC potential of climate in Konya by hours

Konya	Total DFC Potential	Mean DFC Potential	Standard Deviation	Lowest DFC Potential	Highest DFC Potential
[1975,2004]	43700	1456.67	139.85	1159	1746
[2020,2049]	46765	1558.83	126.14	1315	1929
$\Delta$ Difference	3065	102.17	-13.71	156	183

Table 4.12. Numerical analysis of DFC potential of climate in Konya by percentile

Konya	Mean DFC Potential	Relative SD	Lowest DFC Potential	Highest DFC Potential
[1975,2004]	16.62%	9.60%	13.22%	19.92%
[2020,2049]	17.78%	8.09%	15.00%	22.00%
$\Delta$ Difference	1.17%	-1.51%	1.78%	2.09%

For the [2020,2049] period, Konya climate will be able to support direct free cooling for 17.78% of the time on the average, which is an increase of 102.17 hours in mean DFC potential from the control period. A change of -1.51% in relative standard deviation implies fewer fluctuations are expected to occur in year-over-year DFC potentials of Konya with respect to the control period and deviations are approximately 1/12 of the mean DFC potential. The minimum DFC potential of 1315 hours and the maximum of 1929 hours are observed to occur in years 2037 and 2049 respectively.

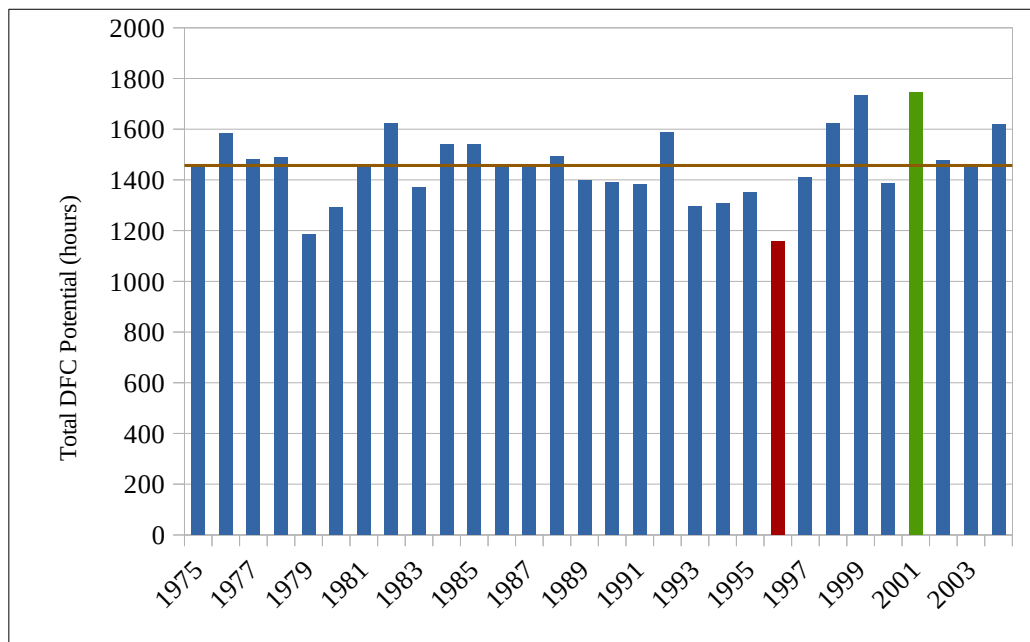


Figure 4.7. Annual number of DFC hours observed during control period of Konya

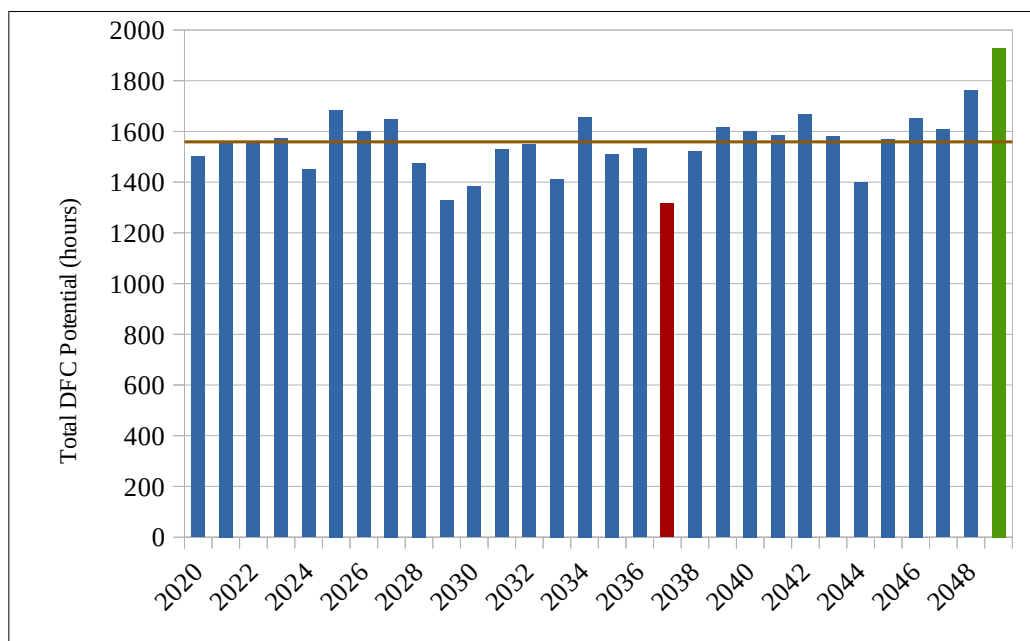


Figure 4.8. Annual number of DFC hours observed during subject period of Konya

#### 4.1.5. Erzurum

Table 4.13. Yearly DFC potential of climate in Erzurum by hours

Year [1975,2004]	Annual DFC Hours	Year [2020,2049]	Annual DFC Hours
1975	870	2020	865
1976	903	2021	911
1977	928	2022	921
1978	863	2023	1021
1979	727	2024	929
1980	895	2025	905
1981	866	2026	975
1982	729	2027	809
1983	678	2028	1050
1984	942	2029	801
1985	890	2030	1101
<b>1986</b>	<b>647</b>	<b>2031</b>	<b>791</b>
1987	879	2032	936
1988	807	2033	858
1989	757	<b>2034</b>	<b>1292</b>
1990	716	2035	828
1991	975	2036	1059
1992	824	2037	918
1993	909	2038	1210
1994	771	2039	1114
1995	954	2040	867
1996	839	2041	1090
1997	946	2042	976
1998	926	2043	1157
1999	1037	2044	837
2000	1055	2045	873
<b>2001</b>	<b>1092</b>	2046	1008
2002	1025	2047	1123
2003	780	2048	1065
2004	963	2049	1228

Table 4.14. Numerical analysis of DFC potential of climate in Erzurum by hours

Erzurum	Total DFC Potential	Mean DFC Potential	Standard Deviation	Lowest DFC Potential	Highest DFC Potential
[1975,2004]	26193	873.10	113.18	647	1092
[2020,2049]	29518	983.93	136.93	791	1292
$\Delta$ Difference	3325	110.83	23.76	144	200

Table 4.15. Numerical analysis of DFC potential of climate in Erzurum by percentile

Erzurum	Mean DFC Potential	Relative SD	Lowest DFC Potential	Highest DFC Potential
[1975,2004]	9.96%	12.96%	7.38%	12.46%
[2020,2049]	11.22%	13.92%	9.02%	14.74%
$\Delta$ Difference	1.26%	0.95%	1.64%	2.28%

During [2020,2049] period, the climate in Erzurum will be able support direct free cooling 11.22% of the time on the average, which is an increase of 110.83 hours in mean DFC potential from the control period. A change of 0.95% in relative standard deviation implies more fluctuations are expected to occur in yearly DFC potentials of Erzurum with respect to the control period and deviations are approximately 1/7 of the mean DFC potential. The minimum DFC potential of 791 hours and a maximum of 1293 hours are observed to occur in years 2031 and 2034 respectively.

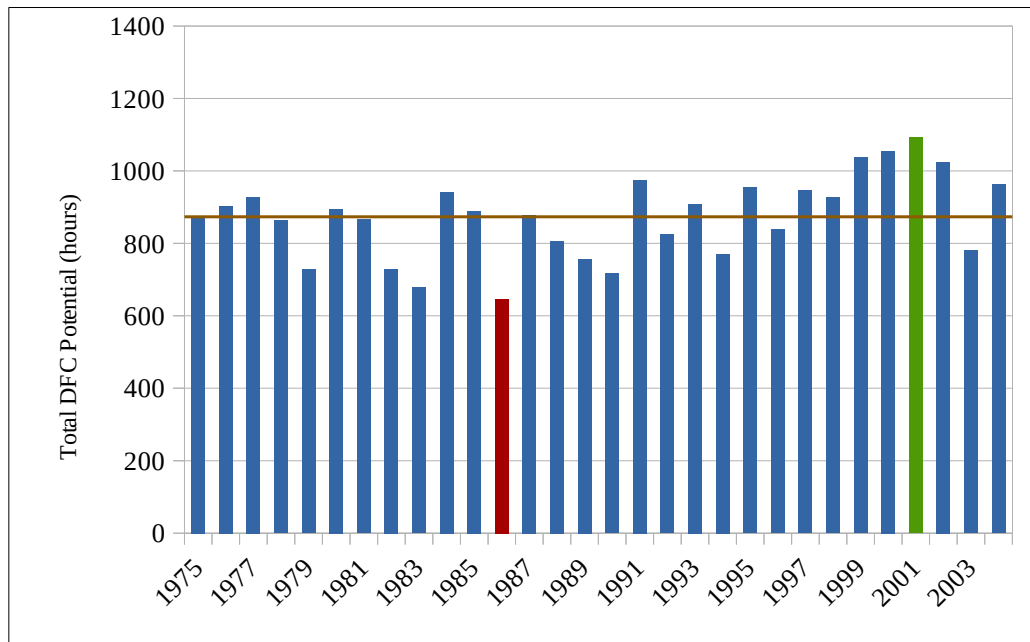


Figure 4.9. Annual number of DFC hours observed during control period of Erzurum

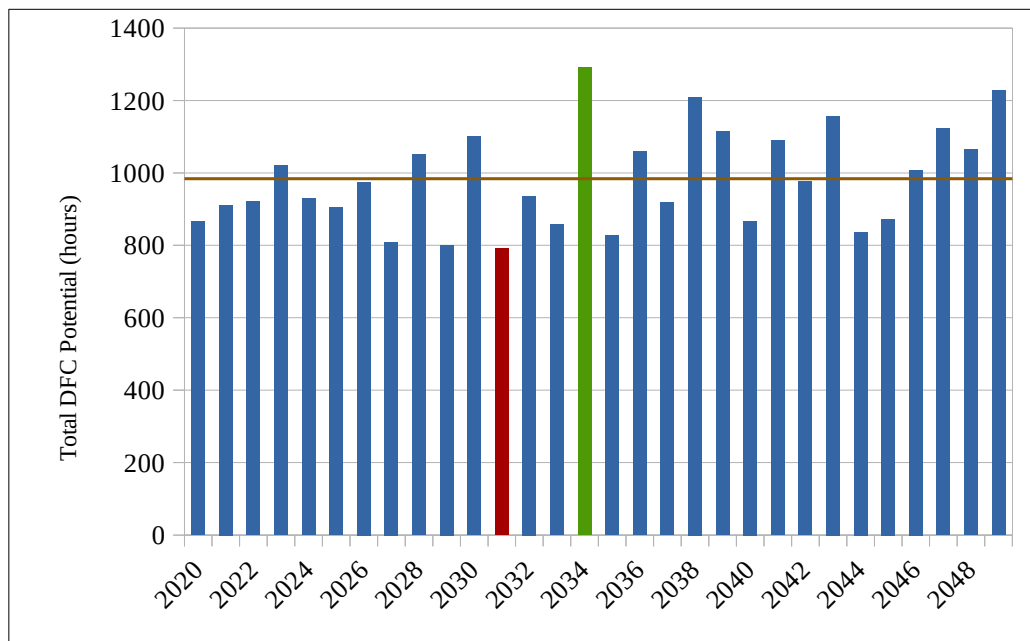


Figure 4.10. Annual number of DFC hours observed during subject period of Erzurum

## 4.2. Comparative Analysis of DFC Potentials

Numerical analysis of hourly and percentile DFC potentials are compared in tabulated form and a column chart representing mean DFC potential within  $\pm 1$  standard deviation in annual hours is provided for control and subject periods. The presentation of results is concluded with a comparison of DFC potentials and relative standard deviations of all cities between each other and cumulatively between periods.

### 4.2.1. Comparison of DFC Potential of Cities for [1975,2004] Period

Table 4.16. Comparison of cities for DFC potential by hours

[1975,2004]	Total DFC Potential	Mean DFC Potential	Standard Deviation	Lowest DFC Potential	Highest DFC Potential
Istanbul	14411	480.37	166.71	166	776
Ankara	36418	1213.93	135.51	966	1511
Izmir	38714	1290.47	247.29	768	1875
Konya	43700	1456.67	139.85	1159	1746
Erzurum	26193	873.10	113.18	647	1092

Table 4.17. Comparison of cities for DFC potential by percentile

[1975,2004]	Mean DFC Potential	Relative SD	Lowest DFC Potential	Highest DFC Potential
Istanbul	5.48%	34.71%	1.89%	8.85%
Ankara	13.85%	11.16%	11.02%	17.24%
Izmir	14.72%	19.16%	8.76%	21.39%
Konya	16.62%	9.60%	13.22%	19.92%
Erzurum	9.96%	12.96%	7.38%	12.46%

During [1975,2004] period, the maximum DFC potential is attained by Konya, followed by Izmir, Ankara, Erzurum, and Istanbul in decreasing order of DFC potential. While Konya, Izmir, and Ankara group together within approximately 3% of mean DFC potential, Erzurum and Istanbul separate significantly from this group and each other. Istanbul is not only observed to have the lowest DFC potential but also has the most significant deviation from its mean and Izmir has the second highest deviation followed by Erzurum, Ankara and Konya, grouping within approximately 3% of deviation in decreasing order.

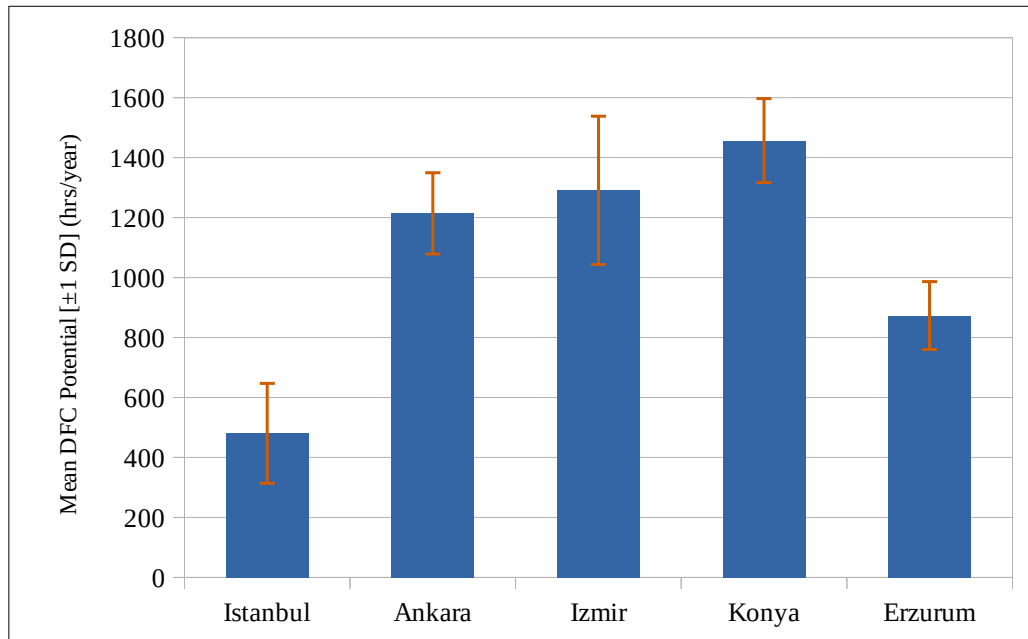


Figure 4.11. Mean DFC potential of cities with their respective standard deviations

#### 4.2.2. Comparison of DFC Potential of Cities for [2020,2049] Period

Table 4.18. Comparison of cities for DFC potential by hours

[2020,2049]	Total DFC Potential	Mean DFC Potential	Standard Deviation	Lowest DFC Potential	Highest DFC Potential
Istanbul	11693	389.77	123.40	158	624
Ankara	38436	1281.20	120.58	987	1570
Izmir	35823	1194.10	211.04	729	1564
Konya	46765	1558.83	126.14	1315	1929
Erzurum	29518	983.93	136.93	791	1292

Table 4.19. Comparison of cities for DFC potential by percentile

[2020,2049]	Mean DFC Potential	Relative SD	Lowest DFC Potential	Highest DFC Potential
Istanbul	4.45%	31.66%	1.80%	7.12%
Ankara	14.61%	9.41%	11.26%	17.91%
Izmir	13.62%	17.67%	8.32%	17.84%
Konya	17.78%	8.09%	15.00%	22.00%
Erzurum	11.22%	13.92%	9.02%	14.74%

For the [2020,2049] period, the maximum DFC potential is attained by Konya, followed by Ankara, Izmir, Erzurum and Istanbul in decreasing order of DFC potential. While Ankara, Izmir and Erzurum group together within approximately 3% of mean DFC potential, Konya and Istanbul separate significantly from this group at opposite extremes. Istanbul is not only observed to have the lowest DFC potential but also has the highest deviation from its mean followed by Izmir and

Erzurum in decreasing order. Ankara and Konya, grouping together within approximately 1% of deviation have the lowest standard deviations in order, observed for this period.

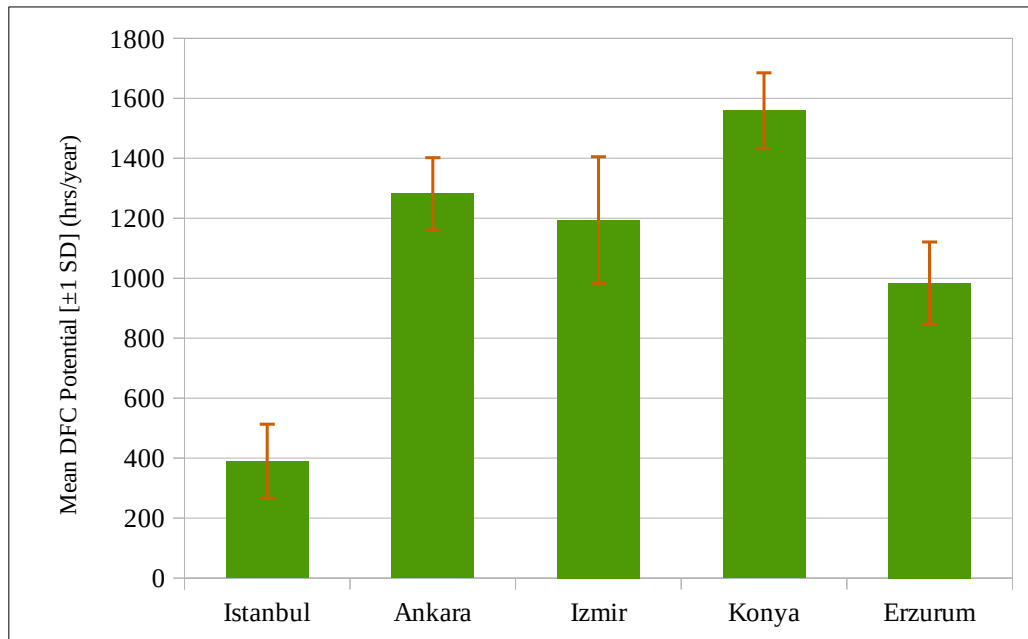


Figure 4.12. Mean DFC potential of cities and their respective standard deviations

#### 4.2.3. Comparison of DFC Potential of Cities Between Periods and Cumulative Potentials

Mean direct free cooling potentials and standard deviations of all cities for control and subject periods are provided together in figures 4.13. and 4.14. respectively. Table 4.18. shows the mean cumulative DFC potentials of cities by periods and associated relative standard deviations. The mean cumulative potential for each period is depicted with horizontal lines in figures 4.12. and 4.13.

Table 4.20. Cumulative mean and standard deviation of DFC potential of cities by period

Period	Cumulative Mean DFC Potential	Relative SD
[1975,2004]	1063	17.52%
[2020,2049]	1082	16.15%
$\Delta$ Difference	19	-1.37%

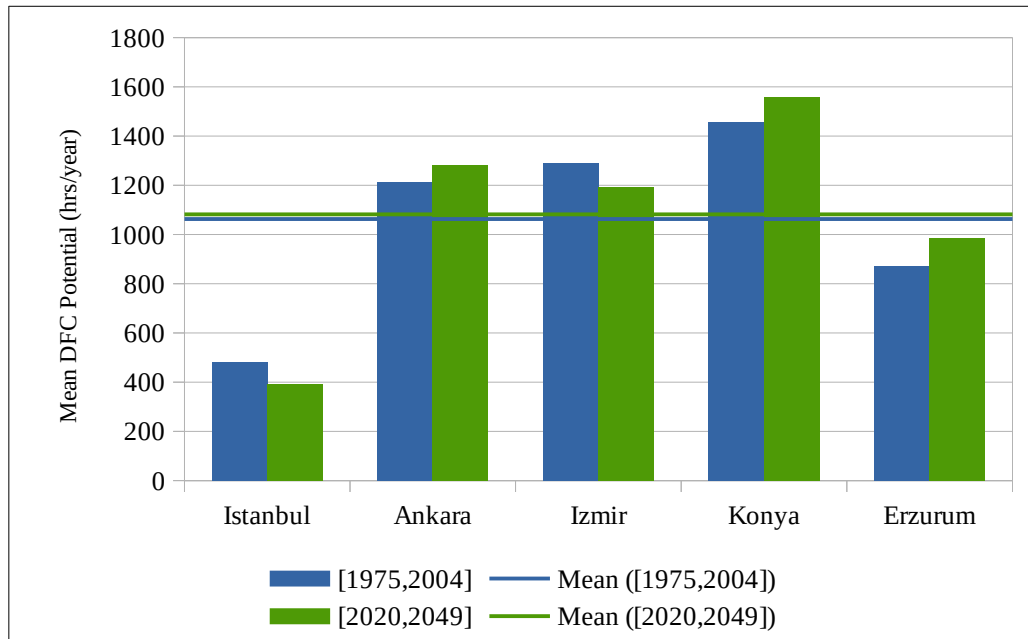


Figure 4.13. Mean DFC potential of cities by periods and period means

Konya, Erzurum, and Ankara have higher DFC potentials in the subject period, while Istanbul and Izmir attain lower potentials with respect to the control period. The cumulative mean DFC potential of cities is observed to increase by 19hrs/year (0.22%) in comparison to the control period.

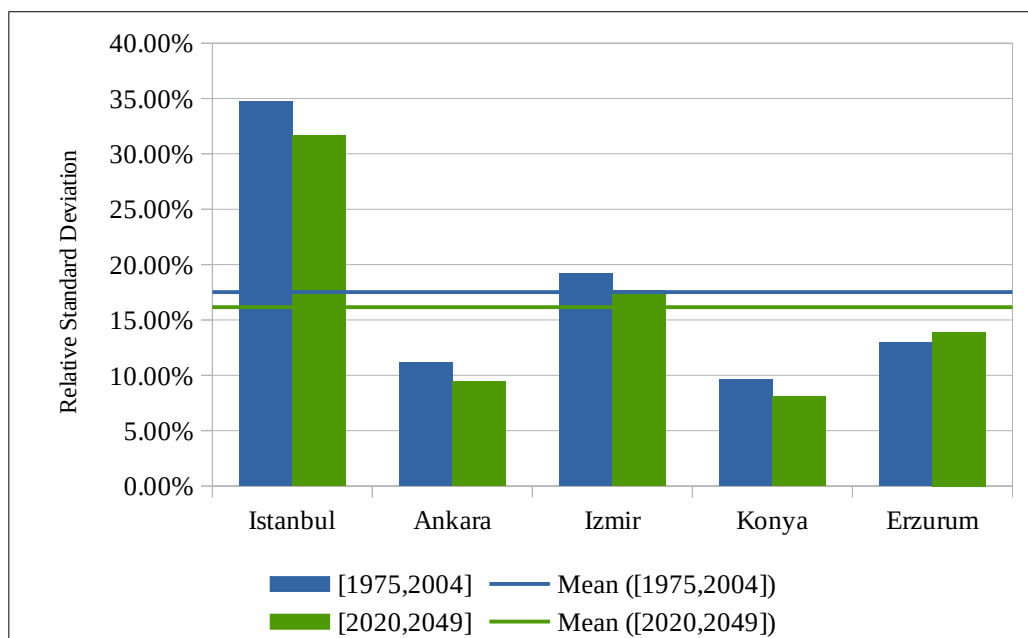


Figure 4.14. S.D. of mean DFC potential of cities by periods and period s.d. means

In the subject period, the deviation from mean DFC potential gets smaller for all cities except Erzurum. The period average of S.D. declines by 1.37% with respect to the control period.

### 4.3. Parametric Analysis of Climate Data by Periods

The total number of hours, that each parameter of climate data violating ASHRAE's recommended environmental specifications for IT equipment in operation (2015), is provided for both control and subject periods of each city. The parameters investigated are not mutually exclusive, therefore their combined affect is presented by the change in DFC potential. The differences between two periods of 262992 hours are provided in absolute number of hours, and percentile changes observed with respect to the control period, in order to reveal the rate of change.

Table 4.21. Parametric analysis of climate data for Istanbul

	DBT < 18°C	DBT > 27°C	DP < -9°C	DP > 15°C	RH > 60%	DFC Potential
[1975,2004]	164114	5186	0	70868	235213	14411
[2020,2049]	154871	9606	0	87139	234279	11693
$\Delta$ Hours	-9243	4420	0	16271	-934	-2718
$\Delta$ (%)	-5.63%	85.23%	-%	22.96%	-0.40%	-18.86%

In Istanbul, the total number of hours that DBT parameter undershoots 18°C is reduced by 5.63%, while temperatures overshooting 27°C is observed 85.23% more frequently, both indicating a warmer climate. Although violations due to relative humidity does not change significantly, an increase of 22.96% is observed in number of hours with dew point temperature greater than 15°C, implying a more humid climate. As a result, DFC potential is decreased by 18.86% with respect to the control period. Figure 4.15. depicts violations are dominated by relative humidity and low temperatures in order.

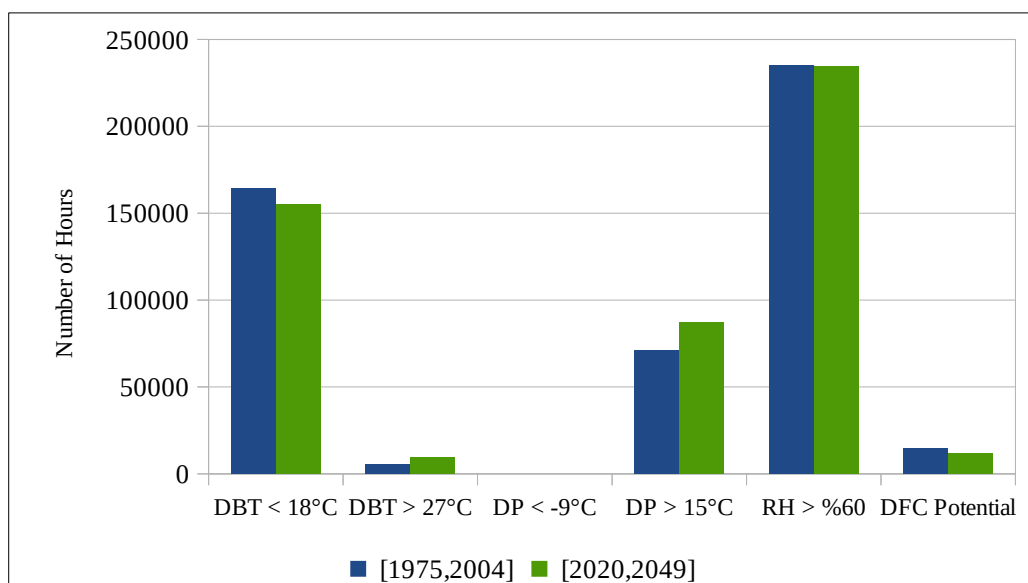


Figure 4.15. Number of hours of violation of ASHRAE's 2015 recommended envelope in Istanbul

Table 4.22. Parametric analysis of climate data for Ankara

	DBT < 18°C	DBT > 27°C	DP < -9°C	DP > 15°C	RH > 60%	DFC Potential
[1975,2004]	207947	16826	3658	475	178707	36418
[2020,2049]	199367	22090	2074	1170	175618	38436
$\Delta$ Hours	-8580	5264	-1584	695	-3089	2018
$\Delta$ (%)	-4.13%	31.28%	-43.30%	146.32%	-1.73%	5.54%

In Ankara, the total number of hours that DBT parameter undershoots 18°C is reduced by 4.13%, while temperatures overshooting 27°C is observed 31.28% more frequently, both indicating a warmer climate. Although violations due to relative humidity decrease by 1.73%, the upper threshold of dew point temperature is violated 146.32% more frequently, while its lower threshold is violated 43.3% less frequently with respect to the control period, implying a more humid climate. DFC potential increases by 5.54% as a cumulative result. Figure 4.16. depicts violations are dominated by low temperatures and relative humidity in order.

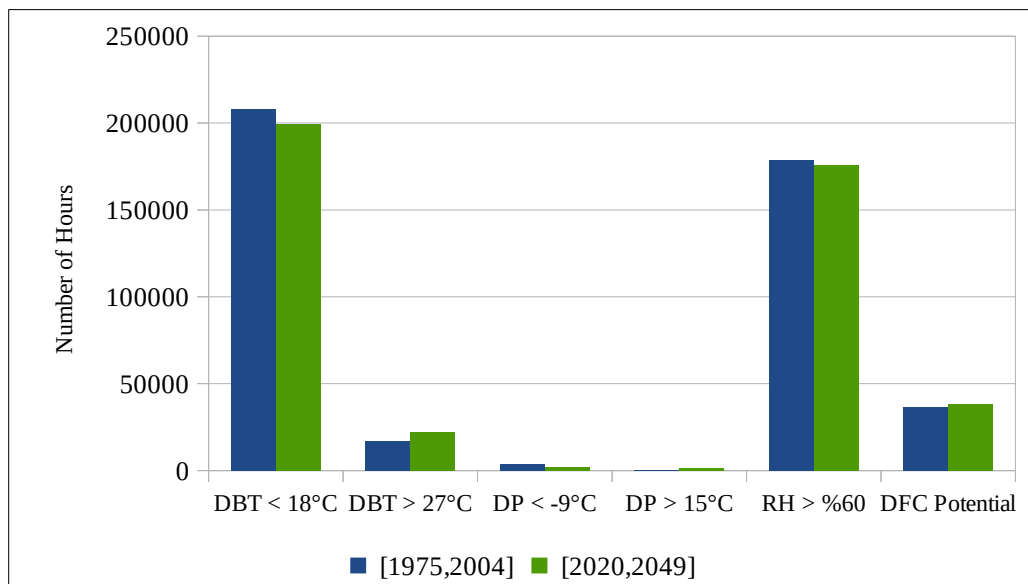


Figure 4.16. Number of hours of violation of ASHRAE's 2015 recommended envelope in Ankara

Table 4.23. Parametric analysis of climate data for Izmir

	DBT < 18°C	DBT > 27°C	DP < -9°C	DP > 15°C	RH > 60%	DFC Potential
[1975,2004]	163656	30919	63	27255	178957	38714
[2020,2049]	153778	37932	30	38538	175255	35823
$\Delta$ Hours	-9878	7013	-33	11283	-3702	-2891
$\Delta$ (%)	-6.04%	22.68%	-52.38%	41.40%	-2.07%	-7.47%

In Izmir, the total number of hours that DBT parameter undershoots 18°C is reduced by 6.04%, while temperatures overshooting 27°C is observed 22.68% more frequently, both indicating a

warmer climate. Although violations due to relative humidity decrease by 2.07%, the upper threshold of dew point temperature is violated 41.4% more frequently, while its lower threshold is violated 52.38% less frequently with respect to the control period, implying a more humid climate. DFC potential decreases by 7.47% as a cumulative result. Figure 4.17. depicts violations are dominated by relative humidity and low temperatures in order.

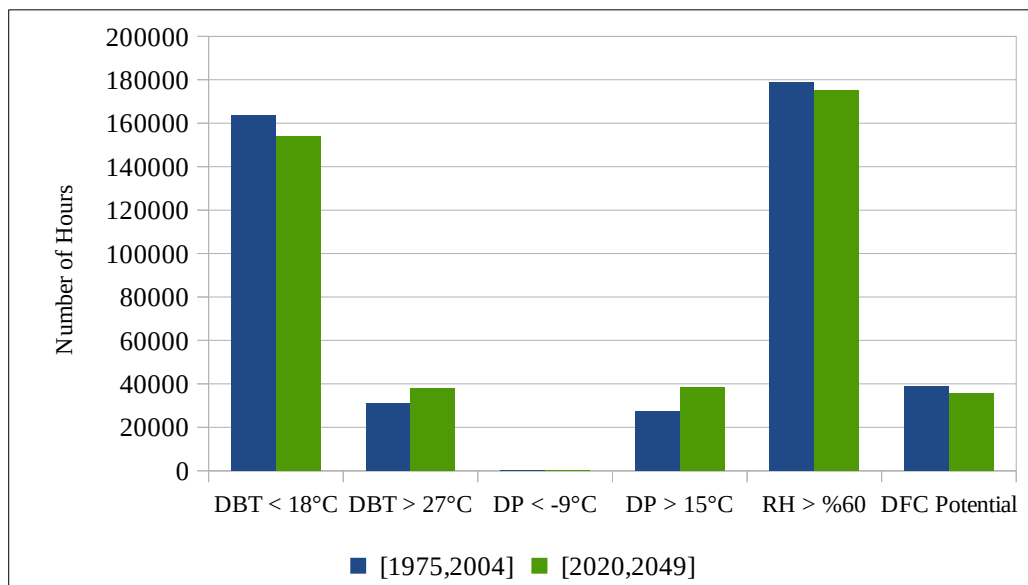


Figure 4.17. Number of hours of violation of ASHRAE's 2015 recommended envelope in Izmir

Table 4.24. Parametric Analysis of Climate Data for Konya

	DBT < 18°C	DBT > 27°C	DP < -9°C	DP > 15°C	RH > 60%	DFC Potential
[1975,2004]	199535	18747	3652	118	152043	43700
[2020,2049]	189816	24351	2377	593	149394	46765
$\Delta$ Hours	-9719	5604	-1275	475	-2649	3065
$\Delta$ (%)	-4.87%	29.89%	-34.91%	402.54%	-1.74%	7.01%

In Konya, the total number of hours that DBT parameter undershoots 18°C is reduced by 4.87%, while temperatures overshooting 27°C is observed 29.89% more frequently, both indicating a warmer climate. Although violations due to relative humidity decrease by 1.74%, the upper threshold of dew point temperature is violated 402.54% more frequently, while its lower threshold is violated 34.91% less frequently with respect to the control period, implying a more humid climate. DFC potential increases by 7.01% as a cumulative result. Figure 4.18. depicts violations are dominated by low temperatures and relative humidity parameters in order.

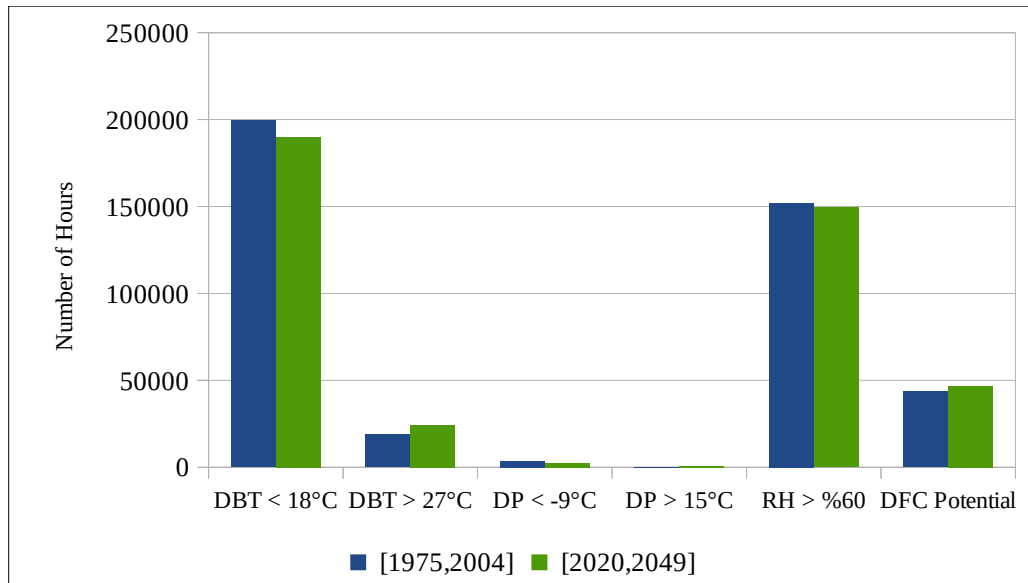


Figure 4.18. Number of hours of violation of ASHRAE's 2015 recommended envelope in Konya

Table 4.25. Parametric Analysis of Climate Data for Erzurum

	DBT < 18°C	DBT > 27°C	DP < -9°C	DP > 15°C	RH > 60%	DFC Potential
[1975,2004]	234103	2543	34185	0	187868	26193
[2020,2049]	227448	5793	28714	3	182997	29518
$\Delta$ Hours	-6655	3250	-5471	3	-4871	3325
$\Delta$ (%)	-2.84%	127.80%	-16.00%	-%	-2.59%	12.69%

In Erzurum, the total number of hours that DBT parameter undershoots 18°C is reduced by 2.84%, while temperatures overshooting 27°C is observed 127.8% more frequently, both indicating a warmer climate together with the decrease of 16% in incidence of dew point temperatures colder than -9°C. The relative humidity violations are observed 2.59% less and cumulatively the DFC cooling potential increases by 12.69% with respect to the control period. Figure 4.19. depicts violations are dominated by low temperatures and relative humidity parameters in order.

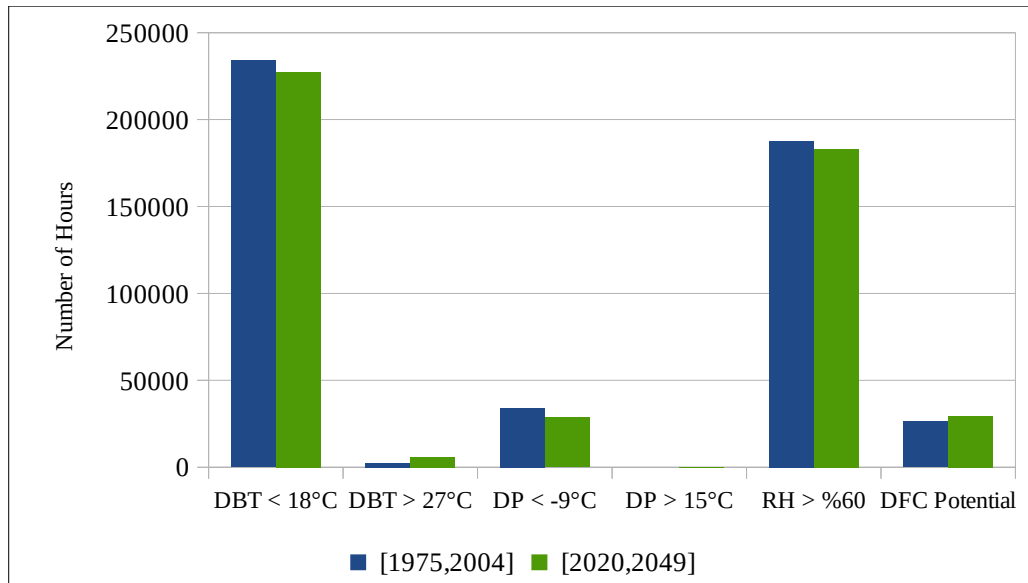


Figure 4.19. Number of hours of violation of ASHRAE's 2015 recommended envelope in Erzurum

#### 4.4. Implications of DFC Potential Investigation

The number of data centers is bound to increase with further reliance on the information technology and data center power densities are on the rise historically, and there already exists a significant amount of data center white space in operation around the globe as well as in native lands of the Turkish Republic. This investigation focuses on cities that are expected to have the most number of data centers in operation due to their development index (Istanbul, Ankara, and Izmir), and also on cities that have future investment potential in data centers. A data center in operation may be retro-fitted with a DFC system while a new data center can be designed to implement DFC system from the ground up and this investigation sheds light on the potential of climate to sustain such cooling systems. The assessment of DFC potentials of geographical regions can help governments in developing sustainable environmental policies and incentives for both readily operating and future planned data centers of the IT industry. Investigation of DFC potential is also beneficial to data center designers and operators of private businesses. The period means of DFC potential in hours per year and associated relative standard deviation together can help investors calculate return on investment and make business decisions, whereas specific annual DFC potential in hours are helpful to operators of data centers and electricity production facilities in foreseeing the supply and demand of energy on a yearly basis.

The direct free cooling potential metric depends on both climate that is ever-changing, and technical specifications of the IT equipment, altered by advances in technology. For this research,

ASHRAE's recommended environmental specification for IT equipment operation (2015) was an invariant and the effects of the changing climate were investigated. Although cumulative mean of DFC potential was not found to be changing significantly, the DFC potentials were decreasing for two cities (Istanbul, Izmir) and increasing for the others (Konya, Ankara, Erzurum). These changes affect the efficiency of a data center using DFC solutions, hence the operational expenses, and can be considered as a measure of sustainability.

The parametric analysis of climate data not only reveals the factors behind changes in direct free cooling potential but also shows which parameters of the climate would be changing in the future and how. Such research approach that include thresholds and boundary conditions and how they are violated can be devised for investigating affects of climate change in other fields of study as well.

This investigation assessed distance weighted averages of four grid points closest to centers of the city under investigation, hence it might not have discovered the full potential of the geographical region a city covers. Hourly interpolation of time series output of the RegCM model with 3 hour intervals was deemed appropriate for the investigation, factoring out momentary drastic changes in weather parameters.

## 5. CONCLUSIONS

The direct free cooling potential of climate for key cities of Turkey are investigated as a measure of energy savings, sustainability, and green production in IT. Accordingly, the climate of Konya was found to have the greatest DFC potential (17.78%) that increases from the control period, and Istanbul was observed to provide the least potential (4.48%) which is in decline compared to the control period. Erzurum was the only city observed to have an increased mean DFC potential and relative standard deviation at the same time for the subject period.

The analysis of non mutually exclusive climate parameters reveal that the dominating factors behind changes in DFC potential of all investigated cities are either dry bulb temperatures lower than 18°C or relative humidities higher than 60%. Cities of Istanbul and Izmir, where leading parameter of violation is relative humidity, are also the cities that have diminishing DFC potentials, whereas Ankara, Konya, and Erzurum cities that violate lower threshold of recommended dry bulb temperature dominantly have their DFC potentials growing in the subject period, although all cities are expected to have warmer and more humid climates in the future. This observation can be attributed to the distance from the seas and other large water bodies, Istanbul and Izmir have sea shores and the other cities investigated are far from large water bodies. DFC potential of climate grows the most in Erzurum (12.69%), followed by Konya (7.01%) and Ankara (5.54%) and diminishes the most in Istanbul (18.86%) and then Izmir (7.47%), all relative to the control period belonging to past.

Findings depicted in Figure 4.13. imply that DFC potential can shift between cities while staying almost constant for both periods, in a way attributable to climate change, and require a higher resolution research over a larger area for a better understanding of DFC potential that climate of the whole country would be able provide in the future. Specifically, classification of geographic regions with diminishing, growing and steady DFC potentials would be of interest for policy and decision making processes with the aim of sustainable and efficient data center operations, leading to lesser CO<sub>2</sub> emissions. Relative standard deviations are of importance for capacity planning and foreseeable operational expenses of data centers, also contributing to policy and decision-making processes for both governmental organizations and privately owned businesses. In this research, Konya and Ankara turned out to be the two cities with the least deviations from their mean direct free cooling potentials.

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## APPENDIX A: ASHRAE THERMAL GUIDELINES FOR DATA CENTER ENVIRONMENTAL CLASSES, 2008 AND 2011

Table A.1. 2008 thermal guidelines for data center environmental classes (ASHRAE, 2008)

Class	Equipment Environmental Specifications for Air Cooling									
	Product Operation <sup>a,b</sup>							Product Power Off <sup>b,c</sup>		
	Dry-Bulb Temperature (°C)		Humidity Range, Non-Condensing		Maximum Dew Point (°C)	Maximum Elevation (m)	Maximum Rate of Change (°C/h)	Dry Bulb Temperature (°C)	Relative Humidity (%)	Maximum Dew Point (°C)
	Allowable	Recommended	Allowable (%RH)	Recommended						
1	15 to 32 <sup>d</sup>	18 to 27 <sup>e</sup>	20 to 80	5.5°C DP to 60% RH and 15°C DP	17	3050	5/20 <sup>f</sup>	5 to 45	8 to 80	27
2	10 to 35 <sup>d</sup>	18 to 27 <sup>e</sup>	20 to 80	5.5°C DP to 60% RH and 15°C DP	21	3050	5/20 <sup>f</sup>	5 to 45	8 to 80	27
3	5 to 35 <sup>d,g</sup>	NA	8 to 80	NA	28	3050	NA	5 to 45	8 to 80	29
4	5 to 40 <sup>d,g</sup>	NA	8 to 80	NA	28	3050	NA	5 to 45	8 to 80	29

a. Product equipment is powered on.

b. Tape products require a stable and more restrictive environment (similar to Class 1). Typical requirements: minimum temperature is 15°C, maximum temperature is 32°C, minimum relative humidity is 20%, maximum relative humidity is 80%, maximum dew point is 22°C, rate of change of temperature is less than 5°C/h, rate of change of humidity is less than 5% RH per hour, and no condensation.

c. Product equipment is removed from original shipping container and installed but not in use, e.g., during repair maintenance, or upgrade.

d. Derate maximum allowable dry-bulb temperature 1°C/300 m above 900 m.

e. Derate maximum recommended dry-bulb temperature 1°C/300 m above 1800 m.

f. 5°C/hr for data centers employing tape drives and 20°C/h for data centers employing disk drives.

g. With diskette in the drive, the minimum temperature is 10°C.

Table A.2. Comparisons of classes defined in 2011 and 2008 thermal guidelines (ASHRAE, 2011)

2011 Classes	2008 Classes	Applications	IT Equipment	Environmental Control
A1	1	Datacenter	Enterprise servers, storage products	Tightly controlled
A2	2008 Classes		Volume servers, storage products, personal computers, workstations	Some control
A3	NA		Volume servers, storage products, personal computers, workstations	Some control
A4	NA		Volume servers, storage products, personal computers, workstations	Some control
B	3	Office, home, transportable environment, etc.	Personal computers, workstations, laptops, and printers	Minimal control
C	4	Point-of-sale, industrial, factory, etc.	Point-of-sale equipment, ruggedized controllers, or computers and PDAs	No control

Table A.3. 2011 thermal guidelines for data center environmental classes (ASHRAE, 2011)

Class <sup>a</sup>	Equipment Environmental Specifications							
	Product Operations <sup>b,c</sup>					Product Power Off <sup>c,d</sup>		
	Dry-Bulb Temperature <sup>e,g</sup> (°C)	Humidity Range, Non-Condensing <sup>h,i</sup>	Maximum Dew Point (°C)	Maximum Elevation (m)	Maximum Rate of Change <sup>f</sup> (°C)	Dry-Bulb Temperature (°C)	Relative Humidity <sup>k</sup> (%)	Maximum Dew Point (°C)
<b>Recommended</b> (Suitable for all A classes)								
A1 to A4	18 to 27	-5.5 °C DP to 15 °C DP and 60% RH						
<b>Allowable</b>								
A1	15 to 32	20% to 80% RH	17	3050	5 / 20	5 to 45	8 to 80	27
A2	10 to 35	20% to 80% RH	21	3050	5 / 20	5 to 45	8 to 80	27
A3	5 to 40	-12 °C DP & 8% RH to 85% RH	24	3050	5 / 20	5 to 45	8 to 80	27
A4	5 to 45	-12 °C DP & 8% RH to 90% RH	24	3050	5 / 20	5 to 45	8 to 80	27
B	5 to 35	8% RH to %80 RH	28	3050	NA	5 to 45	8 to 80	29
C	5 to 40	8% RH to %80 RH	28	3050	NA	5 to 45	8 to 80	29

a. Classes A1, A2, B and C are identical to 2008 classes 1, 2, 3 and 4. These classes have simply been renamed to avoid confusion with classes A1 thru A4. The recommended envelope is identical to that published in the 2008 version.

b. Product equipment is powered on.

c. Tape products require a stable and more restrictive environment (similar to Class A1). Typical requirements: minimum temperature is 15°C, maximum temperature is 32°C, minimum relative humidity is 20%, maximum relative humidity is 80%, maximum dew point is 22°C, rate of change of temperature is less than 5°C/h, rate of change of humidity is less than 5% RH per hour, and no condensation.

d. Product equipment is removed from original shipping container and installed but not in use, e.g., during repair maintenance, or upgrade.

e. A1 and A2 - Derate maximum allowable dry-bulb temperature 1°C/300 m above 950 m.

A3 - Derate maximum allowable dry-bulb temperature 1°C/175 m above 950 m.

A4 - Derate maximum allowable dry-bulb temperature 1°C/125 m above 950 m.

f. 5°C/hr for data centers employing tape drives and 20°C/hr for data centers employing disk drives.

g. With diskette in the drive, the minimum temperature is 10°C.

h. The minimum humidity level for class A3 and A4 is the higher (more moisture) of the -12 C dew point and the 8% relative humidity. These intersect at approximately 25 C. Below this intersection (~25C) the dew point (-12 C) represents the minimum moisture level, while above it relative humidity (8%) is the minimum.

i. Moisture levels lower than 0.5°C DP, but not lower -10°C DP or 8% RH, can be accepted if appropriate control measures are implemented to limit the generation of static electricity on personnel and equipment in the data center. All personnel and mobile furnishings/equipment must be connected to ground via an appropriate static control system. The following items are considered the minimum requirements

1) Conductive Materials

a) conductive flooring

b) conductive footwear on all personnel that go into the datacenter, including visitors just passing through;

c) all mobile furnishing/equipment will be made of conductive or static dissipative materials.

2) During maintenance on any hardware, a properly functioning wrist strap must be used by any personnel who contacts IT equipment.

## APPENDIX B: PSYCHROMETRIC CHART OF ASHRAE 2011 ENVIRONMENTAL ENVELOPES AND SERVER TRENDS VERSUS AMBIENT TEMPERATURE

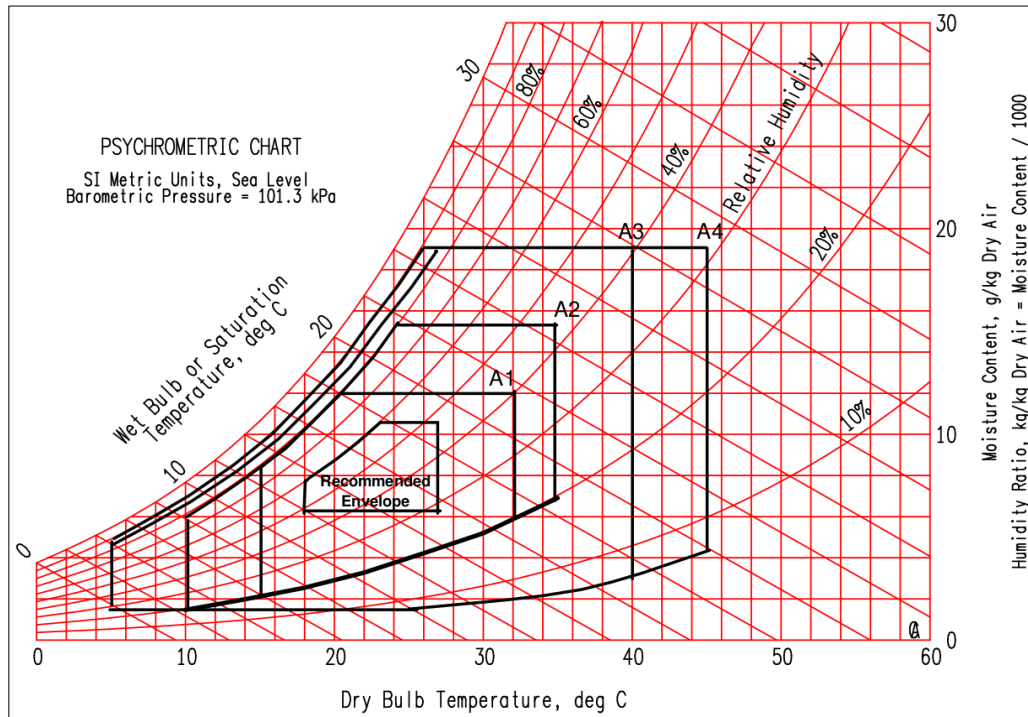


Figure B.1. Psychrometric chart of ASHRAE 2011 environmental classes for data centers (ASHRAE, 2011)

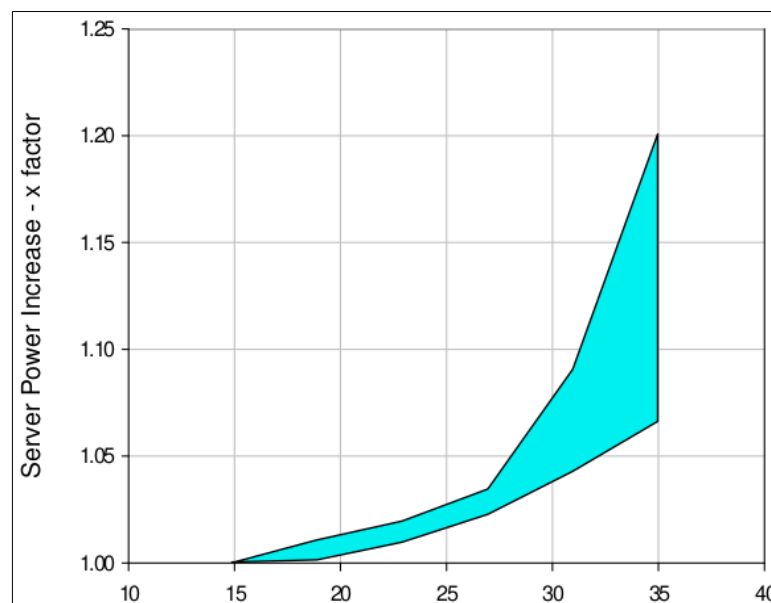


Figure B.2. Server Power Increase vs Ambient Temperature for Class A2 (ASHRAE, 2011)

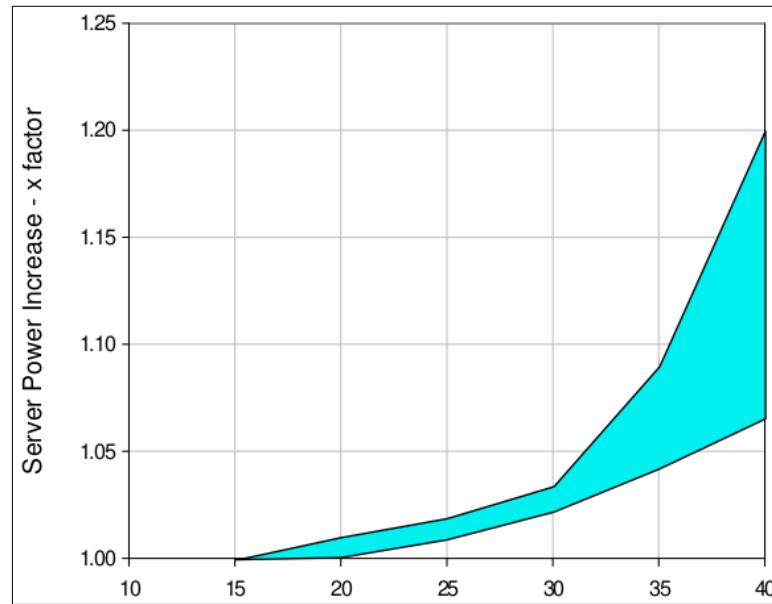


Figure B.3. Server Power Increase vs Ambient Temperature for Class A3 (ASHRAE, 2011)

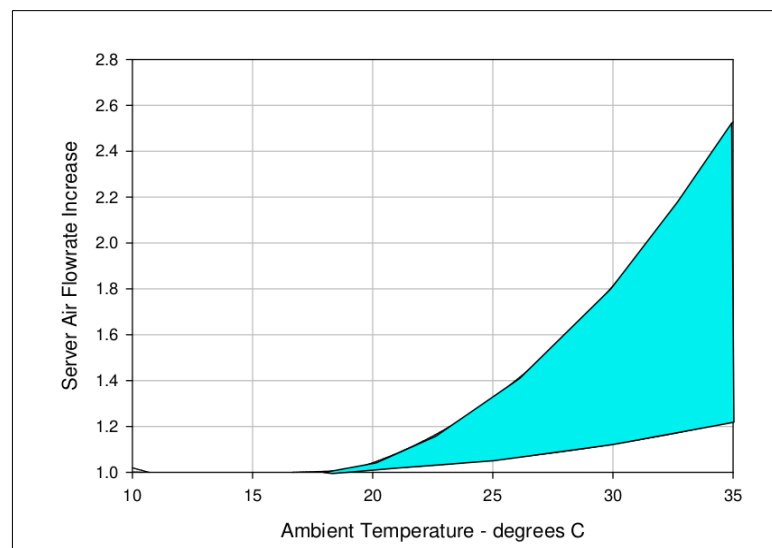


Figure B.4. Server Air Flowrate Increase vs Ambient Temperature Increase (ASHRAE, 2011)

## APPENDIX C: THE GREEN GRID'S 2011 AIR SIDE FREE COOLING MAPS AND THE REFERENCE PSYCHROMETRIC CHART

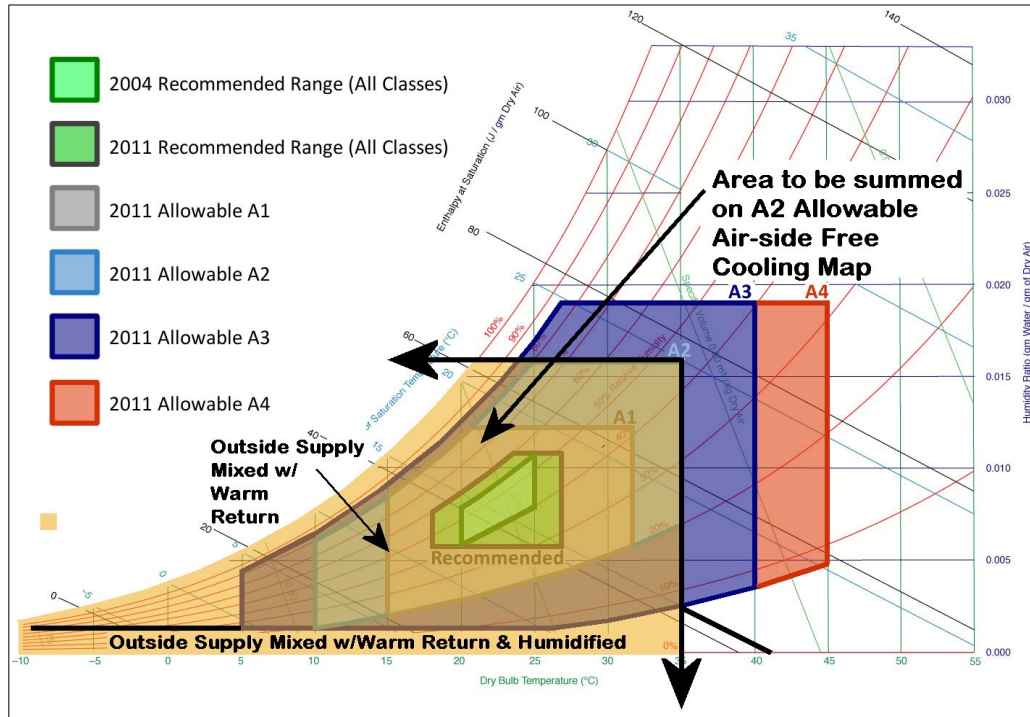


Figure C.1. Graphical representation of the hours summed for the 2009 Green Grid air-side Free Cooling Map, based on ASHRAE Recommended ranges (Green Grid, 2011)

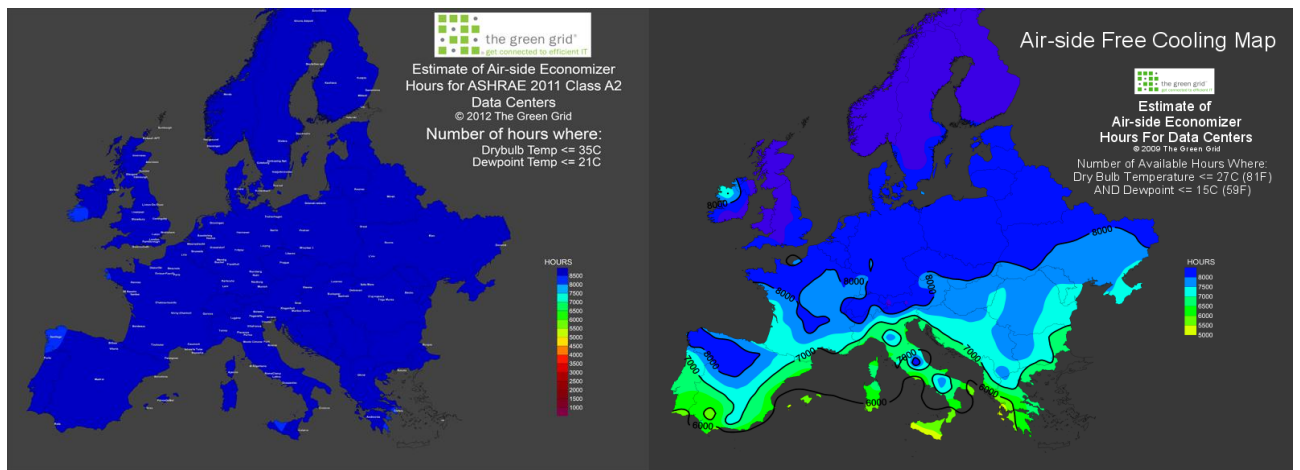


Figure C.2. Green Grid's air-side free cooling maps for Europe (Green Grid, 2011)

## APPENDIX D: THE MAGNUS FORMULA

The Magnus formula (Sonntag, 1990) relates the saturation vapour pressure and dew point. At a temperature  $T$  ( $^{\circ}\text{C}$ ), the saturation vapour pressure  $E_W$  (hPa) over liquid water, is;

$$\text{(Eq.4.) } E_W = \alpha \cdot e^{(\beta \cdot T / (\lambda + T))}$$

For the range from  $-45^{\circ}\text{C}$  to  $60^{\circ}\text{C}$ , Magnus parameters are given by  $\alpha = 6.112$  hPa,  $\beta = 17.62$  and  $\lambda = 243.12$   $^{\circ}\text{C}$ . By restating Eq.4., the dew-point temperature  $D_p$  ( $^{\circ}\text{C}$ ) can be expressed from vapour pressure  $E$ ;

$$\text{(Eq.5.) } D_p = \lambda \cdot \ln(E/\alpha) / \beta - \ln(E/\alpha)$$

Inserting the definition of relative humidity  $RH$  (%), i.e.  $E = RH \cdot E_W/100$ , into Eq. 5. and using Eq.4. leads to calculation of the dew point  $D_p$  from temperature  $T$  and relative humidity  $RH$ ;

$$\text{(Eq.6.) } D_p(T, RH) = (\lambda \cdot \sigma) / (\beta - \sigma) ; \sigma = \ln(RH/100) + (\beta \cdot T / \lambda \cdot T)$$

This formula is a commonly used approximation. Figure D.1. depicts its deviation from the more precise formula described by Hardy in 1998.

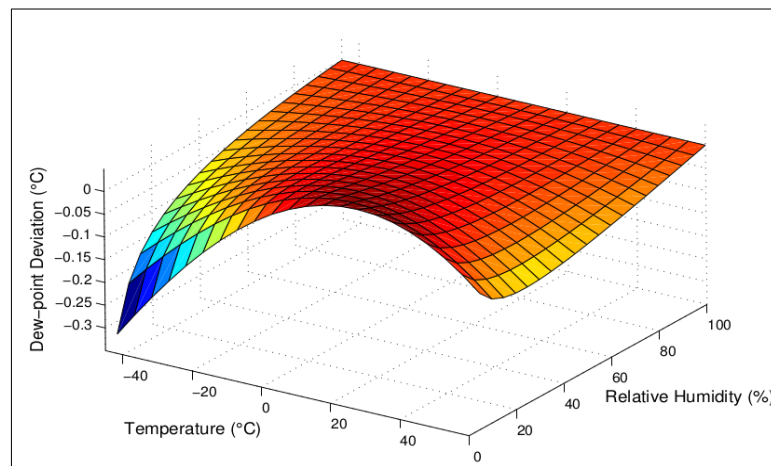


Figure D.1. Deviation of simple Magnus formula from Hardy's precise formula (Hardy, 1998).

Information provided in this appendix is courtesy of the sensor company, Sensirion.