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# Determinants of cities' GHG emissions: a comparison of seven global cities

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**Abstract**: Local GHG inventories provide quite different values of urban carbon footprints. The aim of this work is to identify the determinants of GHGs emissions in order to explain differences, through a comparative analysis of seven global cities – Bangkok, Chicago, London, Madrid, Mexico City, Milan and New York City. Cities have been chosen in order to represent a variety of characteristics and contexts of developed and developing countries and according to data availability.
A first level of analysis regards local GHG emission inventories, which attribute emissions to activity sectors. Sectorial emissions are then evaluated to quantify the relevance of several determinants: climate conditions, urban form, economic activities in place, state of technology, mobility and housing infrastructures and costs, income and life style. These determinants show different weights in influencing behaviours at city level, and ultimately depend on economic, technical, social and cultural factors. Beside a significant role of climate conditions, urban density appears as the main determinant in shaping residential emissions from direct fuel consumption, whereas, for electricity, consumption patterns and technological features of power generation play a major role. For ground transport, urban form affecting mobility patterns and technological features of the vehicle stock stand out as the most significant determinants.

Keywords: climate change, urban emissions, emission indicators

## 1. Introduction

Greenhouse gases result from actions taken at multiple scales, from the local level to the national one. Urban activities are estimated to be responsible for 60% of global energy consumption, an amount forecasted to grow to 73% in 2030 (IEA, 2008). Since '90s, city governments have recognized a potential to reduce GHG emissions within urban areas and the distributed benefits that could emerge from climate-friendly policies in the energy, transportation and waste sectors, such as reduction in local energy costs for families and firms and improvement in air quality (Ostrom, 2009). For these reasons, many local governments have committed voluntarily to emission reduction targets and have endorsed local GHG reduction strategies and plans[9].

The contribution of individual cities to global GHG emissions can be very different. Values published in literature are in the range 2 - 30 $tCO_2$ per capita (Dodman, 2009; Kennedy et al., 2009a; Sovacool and Brown, 2009). For nations, differences in emission levels can be put in direct relation with the degree of development. For cities such a relationship is not always true. Besides of factors typical of each national context, city emissions depend on specific local

[9]The "U.S. Conference of Mayors Climate Protection Agreement" sets the American Kyoto target at city level and is currently endorsed by more than 1.000 municipalities (http://www.usmayors.org/climateprotection/agreement.htm); the European Covenant of Mayors involves almost 2.000 municipalities and commits them in adopting a Sustainable Energy Action plan, with a target going beyond the 20% reduction of GHG emissions by 2020 (http://www.eumayors.eu/).

features. The aim of this paper is to identify the determinants of urban emissions, providing elements to explain differences among the emission levels of cities. The analysis is focused on global cities, which are strategic hubs in the international urban network and are key players in the global fight of climate change.

The sample of cities has been chosen following these criteria: population size over 1 million people; representativeness of different world areas (climate, economic performance); availability of a detailed GHG emissions inventory. Data availability at urban level has strongly conditioned the composition of the sample.

## 2. GHG accounting at local level

Urban GHG inventories are the basis to develop local climate policies. They give a comprehensive overview of emissions in different sectors and highlight the greatest potentials to implement emission reduction measures. In lack of a standard for local inventories, local authorities have developed their own methodology or have relied on guidelines provided by international institutions and city networks. As a result, GHG emission figures that have been attributed to cities are not always comparable. Several authors have pointed out methodological differences among inventories, highlighting that most of approaches used are adaptations of the Intergovernmental Panel on Climate Change (IPCC) guidelines elaborated for national inventories (Kennedy et al., 2009a).

Data availability has been identified as a critical aspect for local inventories: detailed and comprehensive datasets are not always available for cities (Bader and Bleischwitz, 2009). In alternative to bottom-up approaches, which make use of local data, a top-down scaling is sometimes applied: this approach considers emissions estimates derived from national or regional data. Emissions are then scaled to the area of the local inventory, using some measures of activities directly or indirectly related to emissions, such as population figures, energy consumption and mobility demand (Hutchinson, 2002).

Bottom-up urban inventories usually report emissions produced within the city's geographical or administrative boundary by all city actors (the Local Government itself, households, the private sector)[10], applying a "territory principle": GHGs are assigned to the location where gases are emitted (e.g. location of fuel combustion or consumption). In specific cases, an "activity principle" is applied and GHGs are assigned to the location where the activity generating emissions takes place, even if gases are emitted outside the defined activity boundary (e.g. emissions from imported electricity are allocated to the city). A relevant issue in the inventorying process is thus to identify the spatial area and the activities that should be included or not in the estimation, namely to quantify direct and indirect emissions[11].

Studies on cities usually focus on emissions from energy end uses due to urban activities, as energy data are relatively easily available (e.g. from local utilities). This approach often does not take into account emissions associated with the whole energy chain, such as transport losses, refinery emissions or energy conversion losses: this issue should be considered when comparing emission values related to energy uses from different inventories. Kennedy et al. (2009b) show that, if included in the estimation, emissions due to the entire extraction, processing and transportation phases of fuels can increase emissions by 7% to 24%.

Emissions embedded in products and services consumed within the city are more rarely included in urban inventories for the complexity of methods and reasons of data availability: considering embedded emissions would necessitate to take into account their full GHG impact during the complete life-cycle (extraction of materials, production, distribution, use and disposal). Nonetheless several examples of inventories including embedded emissions for cities exist (e.g. the inventory of the City of Paris quantifies emissions associated with the consumption of food, cement and freight transport at city level, Mairie de Paris, 2009).

Another issue that influences the comparability of urban emission values is the definition of sectors within the inventory. In lack of a unique classification, emissions in urban inventories have been sub-divided in sectors with varying levels of aggregation and detail, according also to data availability. The IPCC guidelines for national inventories suggest five main sectors which cover almost all anthropogenic emissions (energy, industrial processes and product use, agriculture, forestry and other land use, waste, "other"),

[10] An inventory may refer to the operational boundaries of the Local Government promoting the climate strategy and focus on emissions caused directly by operations, sources and facilities controlled by the Local Government itself (Bader and Bleischwitz, 2009). As GHGs attributable to Local Governments are usually a small fraction of overall city emissions, operational emissions are most of the times included in broader - geographically based - inventories.

[11] The concept of "scopes", elaborated by WRI within the GHG Protocol Reporting Standard to classify corporate emissions, has been adapted by ICLEI to Local Governments, in order to support them in the categorization of emissions sources. According to ICLEI's protocol, territorial emissions can be distinguished in:
1) Scope 1: Direct emissions, i.e. all GHG that are directly emitted within the territory, such as stationary combustion, mobile combustion, process and fugitive emissions;
2) Scope 2: Indirect emissions which result as a consequence of activities of the territory, such as emissions due to the generation of electricity, district heating, steam and cooling;
3) Scope 3: All other indirect emissions (e.g. landfill, compost emissions) and embodied emissions (e.g. due to the consumption of goods and services within the city) (ICLEI, 2008).

but do not reflect specificities of urban contexts. According to Bader and Bleischwitz (2009), the following IPCC sectors and sub-sectors can represent the majority of urban emissions for European cities: the residential sector, transport, industry, services, industrial processes, fugitive emissions, waste, agriculture and the energy industry[12].

## 3. Comparison of emission values within the sample

Within this paper, attention will be focused on the two sectors that have been proven as the most relevant for the majority of cities: the built sector and transportation. Their relative weight on overall emissions can indeed be quite different among cities. Sovacool and Brown (2009) compared carbon profiles of 12 metropolitan areas worldwide and found that energy and electricity use in buildings accounted for 24% to 87% of total emissions, whereas transport accounted for 5% to 66%.

Table 1 displays emission values for the cities in the sample, expressed in per capita terms in order to facilitate the comparison. For a couple of cities (namely London, Milan) only $CO_2$ emissions are included.

*Table 3.1: Emissions per capita ($tCO_2e$ or $tCO_2$) in the city sample*

| | Year | Total* | Ground Transport | Buildings (of which residential) | Other |
|---|---|---|---|---|---|
| Bangkok (a) | 2007 | 7,55 | 3,74 | 2,63 (0,81) | 1,19 |
| Chicago (b) | 2005 | 12,74 | 2,51 | 8,89 (4,06) | 1,34 |
| London (c) | 2003 | 5,76 | 1,14 | 4,62 (2,23) | 0,00 |
| Madrid (d) | 2004 | 4,98 | 1,55 | 3,12 (1,61) | 0,31 |
| Mexico City (e) | 2000 | 4,20 | 1,66 | 0,83 (0,51) | 1,71 |
| Milan (f) | 2005 | 5,43 | 1,10 | 4,33 (2,70) | 0,00 |
| New York City (g) | 2005 | 7,75 | 1,69 | 6,00 (2,39) | 0,05 |

*Including emissions from ground transport, buildings, waste, industrial sector, agriculture and other, where estimated
Buildings = emissions from residential, commercial, industrial and institutional buildings (the values of emissions from residential buildings are reported in brackets)

Sources for emissions values:
(a) BMA (2008)
(b) CNT (2008)
(c) Mayor of London (2006)
(d) Ayuntamiento de Madrid (2008)
(e) Pardo, C., and Martínez, O. (2006)
(f) IEFE (2009)
(g) Bloomberg, M. R. (2008)

Sources for population values:
(a) BMA website
(b) U.S. census bureau
(c) Office for national statistics
(d) Instituto de Estadística
(e) Sistema Informativo Geográfico, Distrito Federal
(f) Comune di Milano - Settore Statistica
(g) U.S. census bureau

Waste is usually the third most relevant sector in urban inventories and it is also the most complex in terms of emissions estimation, as waste degradation takes place over several years and urban inventories usually report emissions on annual basis. For waste, several estimation methodologies are in use for local inventories, showing discrepancies among them (Kennedy et al., 2009a). Different methodologies have been applied also to cities of our sample and, for this reason, this sector has not been included in this work for analysis. Furthermore, waste covers a minor part of emissions in the overall urban GHG figure in most of the cities we are considering. For Milan and London[13], emissions from waste have not been quantified; for the other cities, this sector covers 1% (New York City), 3% (Bangkok), 4% (Madrid) and 5% (Chicago). Only for Mexico City the relative weight of waste is more significant, 11%, which corresponds for the most part to methane emissions from waste stored in landfills of the Distrito Federal.

In the following paragraphs, emissions of the built sector and transportation will be disaggregated into main factors.

### *3.1. Built sector*

Emissions that are usually reported in urban inventories for the residential and commercial sector are related to buildings operation, and are thus generated by direct fuel consumption and electricity use for various purposes. Several activities may entail either direct fuel use or electricity use according to the technology used, and thus produce emissions reported as direct or indirect within the inventory (Gupta and Chandiwala, 2009): e.g. air-conditioning and space heating can be driven by gas, fuel oil, electricity; cooking stoves can be fuelled by gas, electricity, coal, wood. Broadly, direct fuel consumption is mainly dedicated to space heating and electricity consumption to the use of appliances and lighting. According to the typology of building these two scopes have different weights in the overall energy consumption and respective emissions: direct fuel consumption is more

[12] Global cities are relevant hubs of air traffic. This aspect is sometimes quantified in urban inventories through the estimation of aviation emissions, accounting for flights departing or getting to the city. UNEP, UN-Habitat and the World Bank, in their draft protocol to measure urban GHGs, suggest that emissions due to carry away passengers from a city should be included in every inventory (UNEP, UN-Habitat, World Bank, 2010).

[13] With reference to LECI, the "London Energy and $CO_2$ Emissions Inventory 2003".

relevant in residential buildings compared with commercial ones (45% vs. 31% of overall emissions) and electricity use is far more relevant in the commercial sector (65% vs. 43%) (Gupta and Chandiwala, 2009).

Emissions from direct fuel use are generally estimated applying the appropriate emission factor of each fuel ($tCO_2e/TJ$) to the energy content of fuels consumed (TJ). For electricity, an emission factor representative of the carbon intensity of electricity supplied to the city is applied to the amount of electricity consumed. Usually, the choice of the emission factor for electricity is based on the average emission factor of plants of the main city's supplier. In alternative, the average emission factor of the national supply grid is considered as representative also of the local context. In both cases, emissions associated with power production depend on the technology of plants and the carbon intensity of resources consumed in power generation.

Emissions from the built sector are quantified in the following equation:

$$E_b = \sum_{i=1}^{f} (Q_i \times S_i \times EF_i) + (Q_e \times S_e \times EF_e) \quad (1)$$

Where:

Eb = emissions from energy used in buildings

Qi = quantity of "i" fuel consumed directly for various purposes (i.e. heating, water heating, cooking...) for unit of built surface ($kWh/m^2$)

EFi = emission factor of "i" fuel ($CO_2/kWh$)

Si = floor space consuming "i" fuel ($m^2$)

f = 1, … 8

1 = natural gas
2 = oil
3 = LPG (Liquefied Petroleum Gas)
4 = coal
5 = waste used as fuel
6 = biomass
7 = energy from renewable sources
8 = other

Qe = quantity of electricity consumed for various purposes (i.e. heating, water heating, cooking, air conditioning, use of electric appliances...) for unit of built surface ($kWhe/m^2$)

EFe = emission factor of electricity purchased in the city ($CO_2/kWhe$)

Se = floor space consuming electricity ($m^2$)

Equation (1) expresses emissions as a sum of two products of factors: the first one represents heating emissions as a product of fuel consumption for unit of built surface, for the surface of buildings where fuels are used, for the specific emission factor of each fuel. The second one represents emissions due to electricity consumption as a product of electricity consumption for unit of built surface, for the surface of buildings where electricity is used, for its specific emission factor.

Data on the characteristics of the built stock are not always available at city level and, if they are collected, they are not necessarily comparable between different countries. Only few cities have comprehensive and accessible databases with information on their overall built stock. More data are available for the residential sector, as information on the state of housing are collected by several city departments for policy and planning purposes.

As it was not possible to find data on built volumes or floor spaces for all cities included in our sample, emissions of residential buildings have been related to a proxy, the number of housing units[14]. Emissions of the seven cities have been broken up in factors highlighted in equation (1).

*Table 3.2 Energy and electricity consumption of residential buildings (kWh per housing unit) in the city sample*

| | Qi kWh/number of housing units | | | | | | | Qe kWh / h.u. | Qe+Qi |
|---|---|---|---|---|---|---|---|---|---|
| | gas | oil | coal | RE | waste | biomass | LPG | e.e. | |
| Bangkok (a) (2005) | - | - | 42 | - | - | 17 | 1.135 | 4.657 | 5.851 |
| Chicago (b) (2005) | 32.224 | - | - | - | - | - | - | 5.751 | 37.975 |
| London (c) (2003) | 17.858 | 183 | 15 | - | - | - | - | 4.418 | 22.474 |
| Madrid (d) (2003) | 5.777 | 2.986 | - | 3 | - | - | - | 3.249 | 12.015 |
| Mexico City (e) (2000) | 406 | - | - | - | - | 133 | 3.830 | 1.391 | 5.759 |
| Milan (f)(2005) | 9.063 | 4.169 | - | - | 2.042 | - | - | 2.375 | 17.649 |
| New York City (g) (2005) | 9.427 | 4.856 | - | - | - | - | - | 6.319 | 20.602 |

R.E. = renewable energy

[14] The U.S. census bureau provides the following definition of housing unit, "a house, an apartment, a mobile home, a group of rooms, or a single room that is occupied (or if vacant, is intended for occupancy) as separate living quarters. Separate living quarters are those in which the occupants live and eat separately from any other persons in the building and which have direct access from the outside of the building or through a common hall." http://quickfacts.census.gov/qfd/meta/long_87079.htm

*Table 3.3 Emission factors of fuels reported in the GHG inventories of the city sample*

| | EF ($gCO_2$/kWh) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | gas | oil | coal | RE | waste | biomass | LPG | e.e. |
| Bangkok (a) | | | | | | | | 509 |
| Chicago (b) | 181,2 | | | | | | | 664 |
| London (c) | 187,6 | 270 | 320 | 0 | 0 | | | 430 |
| Madrid (d) | | | | | | | | 404 |
| Mexico City (e) | 201,8 | 278,3 | 340,3 | | | 394,4 | 226,9 | 684 |
| Milan (f) | 198,0 | 262,8 | | | 180 | | | 311 |
| New York City (g) | 181,4 | 270,05 | | | | | | 509 |

(a) Phdungsilp A. (2006); BMA (2008)
(b) CNT (2008)
(c) Mayor of London (2006)
(d) Ayuntamiento de Madrid (2008); values of gas and oil consumption per housing unit are overestimated for Madrid, as the absolute consumption values of these fuels reported in the emission inventory refer to residential and commercial buildings;
(e) Pardo, C., and Martínez, O. (2006)
(f) IEFE (2009)
(g) Bloomberg, M. R. (2008)

Differences in emission factors of fuels, though existing, can be considered of secondary relevance. Data collected for the sample show that differences in fuel consumption are much more relevant. In particular, Chicago shows the highest fuel consumption per housing unit, almost doubling the overall consumption of following cities (New York; London). Milan and Madrid show intermediate values. Cities from countries in development show the lowest values per housing unit (Bangkok, Mexico City). The amount of fuel consumption is deeply influenced by several factors, including specific features of the local context such as climate and the characteristics of buildings (e.g. typology, insulation): in section 4 the factors behind these differences will be analyzed.

As far as emission factors are concerned, values used in the inventories to estimate emissions from energy consumption are similar among them and often IPCC default values are used (e.g. in the inventory of Mexico City and Chicago). Electricity shows the most significant differences in terms of carbon content per unit of energy consumed. The features of power production supplying the city can thus be considered among the determinants of urban emissions and will be specifically considered in section 4.

### *3.2. Ground transport*

Emissions from ground transport can be expressed as a function of several factors representing the amount of transport demanded by residents and city users and the ways through which such demand is satisfied. Grazi and van den Bergh (2008) highlight four "mechanisms of change" concerning GHG policies in the transport sector, which could be targeted through specific measures: (1) transport volume carried out within the city, expressed in trips or kilometers travelled; (2) the modal split, that is the composition of traffic between freight and passenger transportation and the extent to which different modes are employed to move goods or are chosen by people for their travel needs, in particular for passengers ranging from private - motorized or non motorized - transportation to public modes; (3) energy efficiency of motorized modes according to the technological features of the operating vehicle fleet and (4) fuel types used, each characterized by different carbon contents.

Considering that the patterns of freight differ from passengers' transportation, emissions from ground transport are quantified as the sum of the two following equations:

$$(2)\quad Et_{passengers} = \sum_{i=1}^{f} \sum_{j=1}^{m} (T_j \times L_j \times lf)_i \times EF_{ji}$$

$$(3)\quad Et_{freight} = \sum_{i=1}^{f} \sum_{z=1}^{n} VKT_{zi} \times EF_{zi}$$

Where:

Tj = number of passengers' trips with "j" mode
Lj = average length of a single trip with "j" mode (passengers km)
*lf* = load factor of "j" mode (n. passengers/vehicle)
EFji = emission factors of "i" fuel with "j" mode ($gCO_2$/vehicle km)

f = 1, … 6
1 = gasoline
2 = diesel
3 = LPG
4 = electricity
5= other
6 = no fuel

m = 1, … 6
1 = foot
2 = bicycle
3 = subway/rail
4 = bus (and related sub-categories)
5 = passenger car (and sub-categories)
6 = motorcycle (and sub-categories)

VKTzi = kilometres travelled by freight vehicles of "i" fuel and of "z" mode (vehicle km/inhabitants)
EFzi = emission factors of "i" fuel with "z" mode ($gCO_2$/vehicle km)

z = 1,…3
1 = light duty vehicles (and sub-categories)
2 = heavy duty vehicles (and sub-categories)
3 = rail

Equations (2) and (3) express emissions as a product of factors which take in account these four components, highlighting differences in passenger demand from freight.

For passenger transport, demand is represented by two factors, which taken together represent the overall transport volume generating emissions: the number of trips and the average trip length. Each mode is characterized by a specific average trip length, according to the typology of user carrying out the trip (e.g. commuters commonly perform longer trips than city residents) and to the kind of mode (e.g. trips on foot or by bicycle are usually shorter than trips performed with motorized modes). Furthermore, specific urban features can contribute to incentivize shorter or longer trips, according to the urban form and the distribution of activities within the city area. For motorized modes, in addition to transport demand factors, technological features are highlighted through emission factors, which should be differentiated according to vehicle categories (e.g. in Europe, the categories Euro 0,1,2,3 ... ) and to fuels consumed.

For freight, transport volume is represented by vehicle kilometres travelled, resulting from the number of freight vehicle trips for the length of trips.

*Table 3.4: Passengers transport: Number of trips for different modes per inhabitants, average length of trips for different modes and emission factors (EF) for different modes.*

| **Passengers transport** | | **Tj (number of passengers trips per inhabitants per year) [1]** | | | | | |
|---|---|---|---|---|---|---|---|
| | **Year** | **Foot** | **Bicycle** | **Subway/rail** | **Buses** | **Pass. Cars** | **Motorcycles** |
| Bangkok (a) | 2005 | 95,5 (14%) | - | 20,5 (3%) | 252,4 (37%) | 313,8 (46%) | |
| Chicago (b) | 2001 | 58,4 (5%) | 7,2 (1%) | 66,8 (6%) | | 929,4 (88%) | |
| London (c ) | 2003 | 272,0 (21%) | 14,8 (1%) | 222,6 (18%) | 207,7 (16%) | 554,0 (44%) | |
| Madrid (d) | 2001 | 255,5 (26%) | 2,7 (0,3%) | 221,6 (22%) | | 508,4 (51%) | |
| Mexico City (e)* | 2002 | - | - | 150,3 (14%) | 697,7 (64%) | 236,1 (22%) | - |
| Milan (f) | 2005 | 131,0 (10%) | 33,1 (3%) | 238,0 (19%) | 158,7 (12%) | 637,8 (50%) | 75,5 (6%) |
| New York City (g) | 2005 | 708,1 (51%) | 7,3 (1%) | 222,7 (16%) | 135,1 (10%) | 310,3 (22%) | |
| | | **Lj (average length of trips, km) [2]** | | | | | |
| | **Year** | **Foot** | **Bicycle** | **Subway/rail** | **Buses** | **Pass. Cars** | **Motorcycles** |
| Bangkok (a) | 2005 | - | - | - | - | 10,9 | 6,6 |
| Chicago (b) | 2001 | - | - | 10,5 | | 12,0 | |
| London (c ) | 2003 | 0,8 | 3,2 | 15,9 | 3,7 | 11,5 | |
| Madrid (d) | 2001 | - | - | 10,5 - | | 11 | |
| Mexico City (e) | | - | - | - | - | - | - |
| Milan (f) | 2005 | 1,2 | 3,5 | 7 - | | 6,5 | 4,4 |
| New York City | | - | - | - | - | - | - |
| | | **lfj (load factor of j mode (passengers/vehicles) [3]** | | | | | |
| | **Year** | **Foot** | **Bicycle** | **Subway/rail** | **Buses** | **Pass. Cars** | **Motorcycles** |
| Bangkok (a) | | 1 | 1 | - | - | - | 1 |
| Chicago (b) | 2001 | 1 | 1 | - | | 1,1 | 1 |
| London (c ) | 2001 | 1 | 1 | - | 15,0 | 1,34 | 1 |
| Madrid (d) | 2001 | 1 | 1 | - | | 1,32 | 1 |
| Mexico City (e) | | 1 | 1 | - | - | - | 1 |
| Milan (f) | 2005 | 1 | 1 | - | 20,0 | 1,2 | 1 |
| New York City | | 1 | 1 | - | - | - | 1 |
| | | **EF (Emission factors expressed in $gCO_2$ per vehicles kilometres travelled; or $gCO_2$/kWh for subway/rail) [4]** | | | | | |
| | | **Foot** | **Bicycle** | **Subway/rail** | **Buses** | **Pass. Cars** | **Motorcycles** |
| | **Year** | $gCO_2$/ km | $gCO_2$/ km | $gCO_2$/ kWh | $gCO_2$/ km | $gCO_2$/ km | $gCO_2$/ km |
| Bangkok (a) | 2005 | 0 | 0 | 509 | - | - | - |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Chicago (b) | 2005 | 0 | 0 | 664 | - | 579 | - |
| London (c ) | 2003 | 0 | 0 | 430 | 1200 | 176 | - |
| Madrid (d) | 2003 | 0 | 0 | 404 | - | - | - |
| Mexico City (e) | 2004 | 0 | 0 | 684 | 800 | 377 | 67 |
| Milan (f) | 2005 | 0 | 0 | 311 | 1398 | 212 | 89 |
| New York City (g) | 2005 | 0 | 0 | 509 | - | - | - |

[1] [2] Elaborations on: (a) World Bank (2007); (b) UITP (2006) and CNT (2008); (c) TfL (2004); (d) UITP (2006); (e) INEGI (2007); (f) IEFE (2009); (g) MTA (2006)
[3] (b), (,c), (d) UITP (2006), (f) IEFE (2009)
[4] (a) BMA (2008); (b) CNT (2008); ( c) Mayor of London (2007a); (d) Ayuntamiento de Madrid (2008); (e) ISSRC (2004); (f) IEFE (2009); (g) Bloomberg (2008)

*For Mexico City data on foot and bicycle trips are not available.

*Table 3.5: Freight transport: Vehicle kilometres travelled per inhabitants for different modes and emission factors (EF) for different modes.*

| Freight transport | | $VKT_{zi}$ (Vehicle kilometres travelled) | | | | $EF_{zi}$ (Emission factors) | | |
|---|---|---|---|---|---|---|---|---|
| | | L.D.V. | H.D.V. | Rail | | L.D.V. | H.D.V. | Rail |
| | Year | VKT/ inhabitants | VKT/ inhabitants | VKT/ inhabitants | Year | $gCO_2$/ km | $gCO_2$/ km | $gCO_2$/ kWh |
| Bangkok (a) | 2005 | 919,9 | 126,0 | - | 2005 | - | - | 509 |
| Chicago (b) | 2001 | 3.077,5 | 572,6 | - | 2005 | 821 | 1513 | 664 |
| London (c ) | 2003 | 677,5 | | - | 2003 | - | - | 430 |
| Madrid | | - | - | - | | - | - | 404 |
| Mexico City | | - | - | - | | - | - | 684 |
| Milan (d) | 2005 | 471,2 | | - | 2005 | 527 | - | 311 |
| New York City | | - | - | - | | - | - | 509 |

L.D.V = Light Duty Vehicles; H.D.V = Heavy Duty Vehicles
Elaborations on: (a) Takahashi, Sirikupanichkul (2001); (b) CNT (2008); (c ) Mayor of London (2007a); (d) IEFE (2009).

Private cars have been found as the primary source of transport emissions in several urban areas worldwide, even in those cities supplied by a diffused public transport network (e.g. Sovacool and Brown, 2009). Data on ground transport emissions within our sample show that higher emissions values are associated with a pattern of local mobility where private cars and freight transport cover a significant role (e.g. Chicago, Bangkok) and whose vehicle stock is more carbon-intensive. In Chicago, for example, private traffic, both for passenger transportation and for freight, amounts to a higher volume compared to other cities included in the sample, as shown by activity data expressed in equations (2) and (3) (respectively, passenger trips and vehicle kilometres travelled per inhabitant). Passenger cars in Chicago carry on average less people per vehicle than other cities, as represented by data on the load factor, confirming a more intense utilisation of private cars compared to other cities. Furthermore, both the passenger and freight vehicle stock show a more carbon-intensive performance compared to the stock operating in the other cities. Finally emissions from freight amount to high share of transport emissions (Table 3.6). For Bangkok freight travel appears as a major emissions source, also, whereas passenger transport shows low activity values.

Considering cities with the lowest values of ground transport emissions (London, Madrid, Mexico City and Milan), a decisive role in containing emissions seems played, on one side, by a lower carbon intensity in the stock of private vehicles and, on the other side, by the modal share of trips, thanks to the relevance of non-motorized and public transit mobility. For European cities, trips by subway/urban rail and walking play a relevant role, whereas for Mexico City the bus mode, comprising the quota covered by mini-buses, is far more important. Moreover the bus stock of the Mexican capital is less carbon intensive than in other cities. In section 4, urban features influencing the modal split of trips will be analyzed.

*Table 3.6: contribution of freight and passenger traffic to ground transport emissions in the city sample*

| % on transport emissions | Freight | Passengers |
|---|---|---|
| Bangkok | n.a. | n.a. |
| Chicago (b) | 61% | 32% |
| London (c) | 27% | 67% |
| Madrid | n.a. | n.a. |
| Mexico City (e) | 29% | 52% |

| | | |
|---|---|---|
| Milan (f) | 22% | 66% |
| New York City | n.a. | n.a. |

(b) CNT (2008)
(c) Mayor of London (2006)
(e) Pardo, C., and Martínez, O. (2006)
(f) IEFE (2009)

## 4. Determinants of urban emissions

In the previous section emissions were decomposed in factors, that already provide a more detailed view of emissions sectors. Now, urban characteristics that ultimately influence these factors will be identified. These "determinants" of emissions can be broadly grouped in macro-categories: (i) geographical and (ii) morphological, that correspond to where the city is located, how it is built and designed; (iii) infrastructural features and (iv) technological aspects, related to the the state of technology applied in activities generating emissions, such as energy, water, waste management services and transportation; (v) income and more in general the level of economic development and (vi) the typologies of activities that characterize the local economy, which influence overall urban energy consumption and mobility in the metropolitan area; (vii) energy and transportation prices, which influence purchasing choices and consumption behaviours of consumers; (vii) habits of residents and city users. Relations between these elements are quite complex, as they interlink. In the following section, determinants of urban emissions will be analyzed in order to explain different emissions levels among cities. Even if the discussion will be mainly qualitative, some quantitative indicators will be employed.

### *4.1. Geography and climate*

Cities are, first of all, territorial entities, whose geographical location has contributed throughout their history to shape their form and pattern of development (e.g. presence of a river, localization next to the sea, on an island or a flat, hilly or mountain area).

The availability of specific natural resources or territorial features can influence local infrastructures, e.g. for power generation (hydroelectric power generation) and the localization of plants, e.g. landfills and waste-to-power generation plants. Besides, the city's geographical position determines its climate and meteorological conditions and thus the energy needs for heating and cooling throughout the year. Kennedy et al. (2009b) show the relationship between the localization of ten global cities and their means of power generation. Furthermore, the authors highlight a correlation between local climate, expressed though Heating Degree Days, and heating and industrial fuel use in the ten cities.

In section 3 quite different values for residential energy consumption of the seven cities have been found. A necessary premise is that a few cities are characterized by climate conditions that do not require heating (Bangkok, Mexico City). Residential energy use thus represents mainly other final uses (cooking, water heating, use of electric appliances).

In the remaining cities, local climate plays a significant role in shaping residential emissions, as it is shown by the relevant correlation between the residential consumption of fuels and the number of Heating Degree Days of the metropolitan area where the city is located (Table 4.1).

*Table 4.1: residential energy consumption and energy needs in the city sample*

| | Qi (kWh/ h.u.) | HDD* | Qi/ HDD | Qe (kWh/ h.u.) | CDD* |
|---|---|---|---|---|---|
| Bangkok (a) | 1.194 | 0 | | 4.657 | 3.884 |
| Chicago (b) | 32.224 | 3.610 | 8,9 | 5.751 | 461 |
| London (c) | 18.056 | 2.679 | 6,7 | 4.418 | 84 |
| Madrid (d) | 8.766 | 1.891 | 4,6 | 3.249 | 805 |
| Mexico City (e) | 4.369 | 584 | | 1.391 | 245 |
| Milan (f) | 15.275 | 2.157 | 7,1 | 2.375 | 867 |
| New York City (g) | 14.283 | 2.641 | 5,4 | 6.319 | 639 |

*Qi = fuel consumption per housing unit
Qe= electricity consumption per housing unit
HDD= Heating Degree Days
CDD= Cooling Degree Days
Sources: (a), (b), (c), (d), (e), (g): Sivak (2009)
(f) Degreedays.net

In order to compare energy and emission values normalizing the effect of local climatic conditions, the ratio of direct fuel consumption in a housing unit (Qi) and the specific heating needs (HDD) of the city has been calculated. Results confirm the highest energy consumption for Chicago, lower consumption for European cities, in particular for Madrid, and for New York City.

For electricity consumption such climate-correspondence does not remain valid: the quantity of electricity used per housing unit cannot be directly related to cooling needs, expressed by Cooling Degree Days, as the value comprises also the usage of electric appliances, which is influenced by the energy efficiency of the appliances themselves, the level of economic welfare of residents and habits.

Different end-uses of residential electricity can be highlighted in each country according to climate conditions. This factor is in particular of an utmost importance in cities located in areas with a tropical climate, as Bangkok. Almost half of electricity consumption of households in the Bangkok

Metropolitan Area, as assumed in Phdungsilp (2006), is dedicated to air conditioning. In the other cities, this quota is quite limited, as reported in their emissions inventory: in New York City, Mexico City and London, air conditioning covers respectively 5%, 3% and 1% of emissions from residential buildings; in Madrid 0,2% of residential energy consumption. Such data are not available for Milan and Chicago.

### *4.2. Morphology*

City size and shape directly affect overall urban energy consumption and transport volume. As the OECD report "Competitive Cities and Climate Change" points out (Kamal-Chaoui, Robert, 2009), urbanization entails a higher energy demand in absolute terms, but if per capita values are considered a correlation between higher density and reduced electricity demand can be highlighted (e.g. comparing electricity use in countries with similar climate conditions and varying urban density). This could also be due to smaller sizes of urban homes, which require less energy for conditioning and have less transfer area (Gupta and Chandiwala, 2009). Parshall et al. (2009) find that core counties of New York City, the densest in the metropolitan area, show lower energy consumption in comparison with other US urban counties. Authors suggests that the presence of multi-family housing stock and smaller-than-average residential housing units could be the reason of these low energy consumptions values.

Considering the morphology of the city and of the built stock, density can be taken as a proxy of the compactness of the built environment and of the preponderance of multi-family housing (Table 4.2). A correlation can be found in the sample between the degree of density of the urbanized area and the level of residential energy consumption (Qe+Qi): high density appears associated with limited energy consumption (e.g. Mexico City), cities with intermediate values of density have also similar values for energy use (e.g. European cities) and higher energy consumption are associated with low density (e.g. Chicago). Bangkok constitutes a notable exception as, despite low density, it shows quite low consumption values, probably for the absence of heating consumptions.

*Table 4.2: Residential energy consumption and urban form*

| | Qi+Qe | Density (p/ha)* |
|---|---|---|
| Mexico City (e) | 5.759 | 125 |
| New York City (g) | 20.602 | 104 |
| Milan (f) | 17.649 | 72 |
| Madrid (d) | 12.015 | 56 |
| London (c) | 22.474 | 55 |
| Bangkok (a) | 5.851 | 36 |
| Chicago (b) | 37.975 | 15 |

Qi= fuel consumption per housing unit
Qe= electricity consumption per housing unit

*calculated on the urbanized area
Sources: (a) BMA
(b), (c), (d), (f), UITP

Age and typology of buildings have the most significant correlation with their energy performance (CLG, 2006). London and Milan show a quite old built stock, with respectively about 60% and 42% of the housing built before 1950 (Table 4.3). This may entail a worse energy efficiency for their residential built stock in comparison with the other cities.

*Table 4.3: Age of the built stock in the city sample (% of housing units built in each time span)*

| | Before 1920 | 1920 to 1945/50 | 1945/50 to 1970/75 | 1970/75 to 1990 | After 1990 |
|---|---|---|---|---|---|
| Bangkok | n.a. | | | | |
| Chicago (b) | 10 | 21 | 34 | 17 | 18 |
| London (c) | 25 | 34 | 32 | | 9 |
| Madrid (d) | 7 | 15 | 39 | 25 | 15 |
| Mexico City | n.a. | | | | |
| Milan (f) | 15 | 27 | 49 | 8 | 2 |
| New York City (g) | 15 | 34 | 33 | 10 | 8 |

(b), (g), U.S. Department of Housing (2004)
(c) CLG (2010)
(d) Instituto de Estadística (2010)
(f) Comune di Milano (2010)

Chicago and Madrid characterize themselves for the newest built stock, with respectively 18% and 15% of the housing built in the last 20 years.

Nonetheless, the housing built stock in U.S. cities has on average a bigger size in comparison with the other cities (Table 4.4), and this could contribute to entail higher energy consumption in Chicago.

*Table 4.4: Average size of a housing unit in the city sample*

| | Average size Housing Units ($m^2$) |
|---|---|
| Bangkok | n.a. |
| Chicago (b) | 187* |
| London (c) | 87 |
| Madrid (d) | 90 |
| Mexico City | n.a. |
| Milan (f) | 80 |
| New York City (g) | 190* |

*for Chicago and New York City the value is a median and not a mean.

(b) U.S. Department of Housing (2004)
(c) (d) national data reported by Williams K. (2009)
(f) IEFE (2009)
(g) U.S. Department of Housing (2004); another source reports 120 $m^2$ as the average size of an apartment in Manhattan (http://money.cnn.com/2003/10/15/news/economy/realestate_newyork/index.htm)

For what concerns transport, there is a significant relation between higher density, reduced car and energy use per person and low $CO_2$ emission values, as density encourages the use of public transportation (Kenworthy, 2003): higher concentrations of residents and workers help reaching the threshold of profitability of public transport and justify investments in a dense public transport supply, thus leading to a more accessible and diffused network. A sprawled city encourages the use of private vehicles, as the lack of a sufficient number of users leads to a diffused transport demand which cannot be covered entirely by the public transport network.

Increasing urban density has been called upon as a possible strategy for reducing GHG emissions in cities, but significant changes in the urban form can only take place in the long run. A changing in the localization and mix of urban functions (residential, commercial, tertiary, recreational functions) can strongly affect transportation demand. Urban services attract users from the surrounding areas and thus generate a demand of transportation towards and within the city. The spatial distribution of functions determines the spatial distribution of trips and their average length: districts with mixed functions, with easily accessible services and commercial areas next to homes, are more favourable to short trips, which in turn are more suitable for non-motorized modes, helping to reduce emissions from transport.

As in the built sector, also for transportation lower emissions in our city sample are associated with a denser urban environment, confirming that cities characterized by a sprawled development (e.g. Chicago) entail a significant higher use of private motorized modes. Bangkok, once again, is an exception. Although the city with highest emissions within this sector, the car-dependence seems not so relevant as for Chicago (see section 3). Milan also does not confirm the correspondence between density and non motorized mobility, showing a high level of private cars trips and a lower number of trips on foot in comparison with other dense cities.

*Table 4.5: Urban density and modal pattern of trips*

| | **Car trips** | **Foot trips** | **Density (p/ha)** |
|---|---|---|---|
| Mexico City (e) | 236,1 | n.a. | 125 |
| New York City | 310,3 | 708,1 | 104 |
| Milan (f) | 637,8 | 131,0 | 72 |
| Madrid (d) | 508,4 | 255,5 | 56 |
| London (c) | 554,0 | 272,0 | 55 |
| Bangkok (a) | 313,8 | 95,5 | 36 |
| Chicago (b) | 929,4 | 58,4 | 15 |

*4.3. Infrastructure*

The built environment and the transportation system may perform differently in terms of energy use and emissions, according to the kind of infrastructure that lies behind the provision of resources and services. For what concerns buildings, for example, the availability of a district-heating or cooling network can entail significant environmental benefits, as they capture and use heat produced during energy generation thus avoiding the consumption of further fossil fuels. The deployment of such energy infrastructure is in turn favoured by the density and compactness of the built environment, as the concentration of customers provides the necessary conditions for the economic viability of the system (Kamal-Chaoui, Robert, 2009).

For transportation, the choice and use of specific modes by residents and city-users can be limited or favoured by the extent and quality of the transportation supply and infrastructure, e.g. the availability of bicycle lanes, pedestrian space and road pricing systems can encourage non-motorized modes; the extension of the public transport network and the degree of integration among public transportation means is certainly a favourable condition to stimulate people to renounce to private car use.

Table 4.6 shows for London and New York, where diffused underground networks are available, the highest values of transport supply, and for Bangkok a value similar to European cities.

*Table 4.6: Public transport supply in the seven cities*

| | **Annual total public transport VKT per inhabitant** |
|---|---|
| Bangkok (a) | 94 |
| Chicago (b) | 39 |
| London (c ) | 157 |
| Madrid (d) | 85 |
| Mexico City (e) | n.a. |
| Milan (f) | 73 |
| New York City (g) | 123 |

(a) Perera (2006)
(b) (c) (d) (f), UITP
(g) MTA (2006)

Significantly, cities with highest values of passenger cars trips are characterized by lower levels of public transport supply.

*4.4. Technology*

As the estimation of emissions from cities mainly relies on energy use data, carbon intensity of fuels consumed and the technology behind electricity generation supplying city demand are of utmost relevance in influencing urban emissions. Also emissions of the overall "energy chain" - thus evaluated along the entire extraction, processing and transportation phases of fuels - depend on the energy efficiency of plants and the quality of transmission infrastructures.

*Table 4.7: Fuel mix of power generation in the seven cities (or respective countries)*

| | **Bangkok (a)** | **Chicago (b)** | **London (c)** | **Madrid (d)** | **Mexico City (e)** | **Milan (f)** | **New York City (g)** |
|---|---|---|---|---|---|---|---|
| | 2002 (national) | 2005 (regional) | 2005 (national) | 2004 (national) | 2000 (national) | 2005 (urban) | 2005 (urban) |
| Gas | 74% | 2,7% | 37% | 20,3% | 13% | 70% | 72% |
| Coal | 16% | 72,8% | 34% | 28,3% | 7% | | 6% |
| Oil | 2% | 0,4% | 1% | 8,5% | 54% | | |
| Nuclear | | 22,3% | 21% | 22,7% | 3% | | 12% |
| R.S. | 7% | | 4% | 17,9% | 24% | 30% | 8% |
| hydro | 7% | 0,7% | | | 20% | 30% | 8% |
| wind | | 0,1% | | | | | |
| biomass | | 0,3% | | | | | |
| geothermy | | | | | 4% | | |
| Other | 1% | 0,7% | 4% | 2,3% | | | 2% |

R.S. = renewable sources

(a) APEC (2006)
(b) US EPA (2007)
(c) Mayor of London (2007a)
(d) EC (2007)
(e) IEA (2010)
(f) IEFE (2009)
(g) Hammer, Parshall (2009)

Data on the fuel mix of electricity generation have been collected for the seven cities and represent either the mix of sources to produce electricity supplied through the national grid or the mix characterizing "local" power generation plants, which have been considered in the emissions inventories of the cities to estimate the overall GHG figure. Electricity supplied to European cities has on average a smaller carbon content in comparison with the other urban contexts, thanks to a major role of nuclear and renewable sources in the overall mix. This is reflected in lower emission values for buildings, compared to U.S. cities. By contrast, cities reporting the heaviest carbon intensity for electricity (Chicago, Mexico City) show the highest reliance on coal and oil on the overall fuel mix composition. This could contribute to shape a heavier emission level for Chicago.

Further technological issues regard the typologies of appliances, heating systems and vehicles used within the city, whose energy efficiency and fuel mix directly influence energy consumption and emissions of buildings and transportation. The legislative framework, at regional as well as national and international level, can fix standards and regulations which directly target these aspects (e.g. European directives on energy efficiency of appliances and average emission performances of new vehicles).

As far as transportation is concerned, data on the features of the vehicle stocks help interpreting emissions values given in section 3. High emissions values can be related to a very inefficient vehicle stock, as clearly emerges considering Bangkok's commercial vehicles fleet and transit vehicles. Even if new vehicles sold in Thailand are technologically advanced, there is a consolidated practice of refurbishing historic vehicles, maintaining old engines. This practice determines a very low efficiency of the in-use stock (World Bank, 2007). A similar practice is in use for the bus fleet managed by the Bangkok Metropolitan Transport Authority (op.cit).

Cities with the lowest emissions values for transportation are characterized by a newer stock of private vehicles. Furthermore, on average European cars are more fuel efficient than vehicles operating in the other countries (e.g. 12,5 km/l in the EU, in comparison to 9,5 km/l in the U.S. and Thailand, 8,5 km/l in Mexico).

*Table 4.8. : Average age of the private and public stock of vehicles (n. of years)*

| | **Bus (1)** | **Passenger Cars (2)** | **Trucks (3)** |
|---|---|---|---|
| Bangkok (a) | 14 (local) | 7,5 (local) | 12 (local) |
| Chicago (b) | 5,04 (national) | 9,0 (national) | 6,8 (national) |
| London (c ) | 5,9 (national) | 5,9 (national) | n.a |
| Madrid (d) | 6,3 (national) | 8,9 (national) | n.a |
| Mexico City (e) | n.a. | 6,1 (local) | n.a |
| Milan (f) | 6,3 (local) | 8,8 (national) | 7,2 (local) |
| New York City (g) | 7,4 (local) | 9,0 (national) | 6,8 (national) |

(a1), (a3) World Bank, 2007; (a2) DIESEL, 2008
(b1), (b2), (b3) BTS, 2006
(c1), (d1), (f1) UITP, 2007; (c2), (d2), (f2) EEA, 2005
(e2) ISSRC, 2004
(f3) ACI, 2009
(g1) MTA, 2006; (g2), (g3) BTS, 2006.

### *4.5 Economic activities in place*

Urban economy contributes to shape the overall GHG emissions of a city, according to the typologies of activities in place. In global cities, urban functions are predominantly service-related, often including advanced sectors - accountancy, law, finance, banking, research, and this is reflected also in their emissions levels.

Emissions from the tertiary sector usually appear in urban inventories through the energy uses they entail, i.e. in buildings and transports, and share some determinants with the residential sector. Some features of the built stock, as for example buildings typologies, sizes of commercial units, efficiency and types of heating and cooling devices, could be explored to evaluate which service activities contribute mostly to urban emissions. Services and jobs located in the city attract users and commuters from peripheral areas, stimulating ground transport, but, as global cities are nodes of a international urban network and may host specialized functions, they also have wider basins of attractiveness - the region, the whole country, foreign countries - according to the typologies of services provided and their degree of specialization.

In specific cases cities can be characterized by the presence of manufacturing activities, covering different quotas of overall emissions. In emerging countries, manufacturing activities are still located in urban contexts and, for their relevant energy consumption levels, they represent a majority of the city's emissions[15].

The cities in our sample are all ranked in international classifications of global cities as preeminent centres of economic activity. London and New York have a recognized primary role in the global urban network showing the highest level of integration and gaining the highest world city status, Alpha++ cities, in the classification of the GaWC[16]. The other cities, according to GaWC ranging from the status of Alpha + to Alpha-, all represent important urban areas linking major economic regions into global economy, with a relevant provision of advanced services. Cities of our sample located in emerging economies, Bangkok and Mexico City, are both administrative poles within their countries and represent a significant share of the overall national product.

As emerges from data on the distribution of employees within the primary, secondary and tertiary sectors, these statuses correspond to a mainly service oriented urban economy. Looking at advanced services, in London 30% of employee jobs are in the financial and business sector, in Milan 33,5% is covered by research, information technology and business activities. The financial sector is now dominating also Bangkok's economy, that in the last decade has experienced a strong change in its employment structure, with manufacturing workers decreasing since the 1990s (Nakagawa, 2004).

[15] As Dodman highlights (2009), the industrial sector weighs 65% on Shanghai's emissions and 80% on Beijing's. For countries whose manufacturing activities have been relocated, or moved out of urban areas, the relative weight of the industrial sector for cities is quite more limited. For example for Athens, Turin and Frankfurt emissions from industrial processes amount to about 10% of the total, as reported in Kennedy et al. (2009a).

[16] Globalization and World Cities Research Network, which focuses on the study of external relations of world cities and their connectivity.

*Table 4.9: Employment distribution of resident population (%)*

| | Services | Manufacturing | Construction | Agriculture |
|---|---|---|---|---|
| Bangkok | n.a. | n.a. | n.a. | n.a. |
| Chicago (b) | 82 | 13 | 5 | 0,1 |
| London (c ) | 90 | 5 | ? | 0 |
| Madrid (d) | 76 | 13 | 11 | 0 |
| Mexico City (e) | 81 | 12 | 5 | 0,4 |
| Milan (f) | 82 | 14 | 4 | 0,1 |
| New York City (g) | 89 | 7 | 4 | 0,1 |

(b) U.S. Census Bureau
(c) GLA (2007)
(d) Instituto de Estadística
(e) INEGI
(f) AMA (2006)
(g) U.S. Census Bureau

The weight of emissions from the industrial sector is limited (4% in Chicago, 7% London, less than 1% Madrid), except for Mexico City (22%). Despite a service-oriented distribution of jobs, in the Federal District of Mexico City factories operating in the chemical, food, beverage and tobacco, machinery, metal products and equipment transport industries are located.

*4.6. Income*

Based on IEA data, Gupta and Chandiwala (2009) report a correlation between building emissions and levels of socio-economic development, showing higher per capita buildings emissions in industrialized countries; similarly, Croci et al. (2009) find in a limited sample of cities that buildings emissions are higher for cities in industrialized countries. Other comparative papers have found an influence of economic factors on heating and industrial fuel use, suggesting that personal income may be associated with larger sizes for homes or modify the levels of thermal comfort required by city residents (Kennedy et al., 2009b).

Within our sample, a relation between emissions in the residential sector and the level of economic welfare, expressed by GDP per capita, is valid, at least for cities in developed countries. Bangkok's emissions are maybe affected by an up-wards effect caused by the relevant electricity consumption, in response to the local tropic wet and dry climate which characterizes its position.

For what concerns transport, even if economic welfare is generally associated with increased car ownership and higher motorization, previous studies have found no statistical correlation between per capita private transport energy use and GDP per capita, suggesting that policy, physical differences between cities and personal choices are more relevant in influencing the use of different transport modes

(Kenworthy, 2003). Nevertheless, in developing countries a certain correlation between income level and transport modes may be identified, as lower income people can often rely only on non-motorized transport modes (e.g. slum dwellers of large metropolitan cities experience limitations to their mobility as they cannot afford the costs of private of even transit modes and housing is often located in areas that lack connection to the urban transportation network, Bertaud et al., 2009). Rapidly developing countries are experiencing extraordinary private motorization growth rates associated with rising incomes (e.g. Lebel et al., 2007, on Asian countries), and this is also entailing a significant growth of emissions in the transportation sector, even if for lower income groups non-motorized modes still constitute a relevant part of private mobility (op.cit.).

On the contrary cities, which are characterized by high levels of per capita income, can have high share of public transit and low emission transport modes, and this seems confirmed in most of the cities in our sample.

*Table 4.10: urban GDP and emissions*

| | GDP p.c. (000$)* | Buildings | Transport |
|---|---|---|---|
| New York City | 52,8 | 6,00 | 1,69 |
| London | 46,2 | 4,62 | 1,14 |
| Chicago | 45,6 | 8,89 | 2,51 |
| Milan | 35,6 | 4,33 | 1,10 |
| Madrid | 29,0 | 3,12 | 1,55 |
| Bangkok | 15,0 | 2,63 | 3,74 |
| Mexico City | 14,3 | 0,83 | 1,66 |

*at Purchasing Power Parity
OECD, 2006 (except for Bangkok: PWC, 2007)

### *4.7 Prices*

Energy prices and the relative price of alternatives to satisfy urban needs affect local emissions, also according to the price elasticity of demand of consumers towards specific goods and services.

Prices are actually composed by taxes and charges applied by several institutional levels: examples in the transport sector are taxes on automotive fuels, which are usually set at national level, and road pricing systems, which apply a fee on vehicle users according to defined criteria (e.g. when entering a defined area) and are usually defined by local authorities.

Reactions to changes in energy prices can take place in the long run and in a short term period, also depending on the type of investments that they imply for the consumer. In the building sector, for example, home refurbishment and renovations are usually longer-term investment decisions. In transportation, changes in fuel prices cause shifts of consumers towards alternative fuels or different car types, varying the average emission contents of the vehicle stock; variations in the relative price of public transportation in comparison to private motorized modes can cause a shift in the modal pattern of mobility in a short term view.

As highlighted in Kamal-Chaoui, Robert (2009), behaviours respond to incentives that attribute a price to GHG intensive and unsustainable practices. Such measures can thus be used as a stimulus to change and be an effective part of climate change strategies defined by city governments.

### *4.8 Culture*

Different attitudes exist towards energy consumption and energy saving, as appears for example when buildings are operated. According to Gupta and Chandiwala (2009), even if there is lack of precise information about variations in energy use due to behaviours, energy data show that occupants of identical homes can vary the final energy use of a factor of two or three with different energy patterns use. Furthermore, individual aspects affect the choice of more efficient electric appliances, the attitude towards the refurbishment of homes (i.e. investments in insulation of walls, more efficient windows, micro-renewables for residential use) and the level of desired thermal comfort. Personal and cultural factors can also influence the choice of specific transport modes, e.g. cycling habits, despite unfavourable climate and territorial conditions.

Even if climate change has gained increased importance in the global agenda as an urgent issue, it is difficult at the moment to estimate how each underlying motivation contributes to more or lesser environmentally-aware attitudes. Furthermore, individual worries about environmental issues are deeply related to people’s values.

The WRI (Earthtrends, 2010) underlines how access to information is a determinant of good environmental governance, as it provides decision-makers and the public opinion with the necessary tools and knowledge to understand environmental issues and trends. In low income countries such access is often denied to a significant share of population, for several reasons: limited investments, lack of infrastructure, an unfavourable socio-economic environment. Statistics are available on the access to ICT and information media, showing how worldwide access can vary significantly in its extent. Quoting a few data related to internet, which we may consider as a primary and up-to-date source on environmental information, values range from 500-750 people on 1.000 with access to internet respectively in Europe and North America, to 100-200 in Asia and Central America.

Furthermore, educational and awareness campaigns are determinant to rise people’s sensitiveness towards climate change and the role that cities can play in reducing emissions. All climate plans published by local authorities of the seven cities considered in this analysis foresee a variety of measures to address different stakeholders, in order to provide them with incentives and information which can orientate them towards less carbon-intensive lifestyles.

## 5. Conclusions

We have compared GHG emissions attributable to the residential sector and ground transport of seven global cities, chosen for their different characteristics in terms of climate conditions, urban form and level of economic performance, making use of the values published in their emissions inventories. Emissions have been disaggregated into basic factors (indicators of activity; emissions factors) and have then been "read" through a set of urban features - territorial, economic, technical, social and cultural - in order to verify which elements can be considered as "determinants" of emissions in each city.

Looking at residential emissions, a primary determinant is climate, which entails more relevant energy consumption levels for those cities having higher heating needs (e.g. Chicago, London, New York City) or cooling needs (Bangkok, as emerges from electricity consumption levels).

In similar climate conditions, nonetheless, levels of direct fuel consumption vary significantly in relation to the features of the residential stock. Cities with a dense built environment consume lower energy quantities per housing unit. This stands out for example when comparing two cities as Chicago and New York City, which, beside climate, also share similar conditions in terms of economic welfare and the technological features of appliances in use. Furthermore, in similar climate conditions, a better energy efficiency of the built stock seems relevant in explaining lower energy consumption level: comparing energy use in Madrid and Milan, the former is characterized by a relatively newer built stock, which shows better energy performances than Milan's residential stock.

Electricity consumption, on the contrary, seems strictly related with the level of economic welfare, as emerges considering the significant quantities of electricity consumed in Chicago, New York City, London. This could be linked to a larger diffusion of appliances and electric devices than lower-income cities. A better energy efficiency of newer appliances could be outweighed by a significant rise in the number, and variety, of appliances in use. Further data at city level are needed to support these observations.

Looking at ground transport, the form and density of cities appear as determinant in shaping modes in use and emissions: high density enables cities to satisfy a relevant quota of passenger demand through non-motorized transport (e.g. New York City) and, thanks to a diffused network, through public transit (e.g. New York, London, Mexico City, Milan). Cities with lower density show, on the contrary, significant use of private cars and higher emissions. Features of the vehicle stock are determinant in particular for cities where the stock is very inefficient (e.g. Bangkok) or very efficient (e.g. Milan). In the first case, it contributes to entail significant emissions levels, and its effect is probably emphasized by difficult traffic conditions; for Milan, a vehicle stock characterized by a relatively low carbon-intensity outweighs the significant use of private cars and contributes to maintain low emissions values.

Finally, a particular focus should be dedicated to freight transport, whose role appears significant in cities with higher emissions (Chicago, Bangkok). This sector could be targeted through specific policies concerning the overall truck activity (e.g. in Chicago trucks cover a greater share of vehicles kilometres travelled than nationally – 52% vs. 41%, CNT, 2008); or targeting vehicle efficiency and carbon performances of the commercial vehicle fleet (e.g. in Bangkok, limitations to freight transport within the city have been in place for several years, but they have incentivized the use of smaller vehicles, which have been found comparatively less efficient - World Bank, 2007).

The review has shown how each determinant can act differently according to the city and the local context. Further efforts should be dedicated to deal more significantly with specific determinants – such as technological features of appliances and heating systems, prices, in particular how car usage can be discouraged through road pricing systems, and the influence of culture and habits.

The consistency of urban data used for comparison (e.g. methodology, assumptions, geographical coverage), which is probably the main bias of this work, should also be deepened. In several cases, the lack of sources of information and of standardized data have not enabled a more detailed comparison among the cities in the sample.

Nonetheless, the work has developed a detailed insight into two significant urban emissions sectors and main emissions components. Such a view can help a city in identifying where effective levers are available at the local decision-making scale, and which levers are more suitable to be integrated in the city's planning strategies. A possible development of this work could focus on linking determinants to policy measures, in order to provide local authorities with a complete overview of their leeway to act in GHG emitting sectors.

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# Impact of solar activity on climate changes in Athens region, Greece

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**Abstract:** The scope of this work is to study the role that the solar weather plays in terrestrial weather. For this reason we study the effect of the solar activity on the climate changes in Greece. In the current work we look for possible correlation between the solar activity data spanning the years from 1975 to 2000 and the meteorological data from two weather stations based inside the city of Athens, Greece (New Philadelphia) and in greater Athens in the north of Attica (Tatoi area). We examine the annual variations of the average values of six meteorological parameters: temperature, atmospheric pressure, direction and intensity of wind, rainfall and relative air humidity. The solar data include decade variations, within the above period, of the solar irradiance, mean sunspot number between two solar cycles, magnetic cycle influence, and solar UV driving of climate (radio flux).

**Keywords**: Climate changes, indicators, solar activity

## 1. Introduction

The Sun, the only star of our planetary system, is the main source of energy supply for Earth. The Sun is a unique laboratory of magnetized plasmas. Intense outflows of ionized particles, mostly protons and electrons in the interplanetary space, form the solar wind. An increase in solar activity (for a simplified picture this implies more sunspots) is accompanied by an increase in the solar wind. In turn the solar wind forms the heliosphere in which Earth and the rest of our planets bathe. A more active solar wind and stronger magnetic field reduces the cosmic rays striking the Earth's atmosphere. The ionizing solar particles enter the magnetosphere, ionosphere and upper atmosphere, producing auroras, magnetic-storms and other phenomena known as space weather. These changes in the solar radiative output have an impact on the terrestrial energy balance and can affect the chemistry of the stratosphere.

Observations and theory indicate that the Sun is variable on all time scales, from seconds to centuries depending on the time-scale of interest. The most common cycle of the solar variability is the ≈11.1 yr cycle (the average value of 9–13 years), or sunspot cycle. This is the periodicity between successive manifestations of the solar activity. When the inversion of polarization of the polar magnetic field on the Sun is considered the period of variability has a 22-year period. That is because the magnetic field of the Sun reverses during each sunspot cycle, so the magnetic poles have the same charge (positive/negative) after two reversals. There are longer periods than these spanning 80–100 years.

All solar phenomena, relevant to the terrestrial climate (e.g. solar irradiance variations, coronal mass ejections etc), are magnetically driven. Therefore a better understanding of the Sun-Earth system requires a good knowledge of the Sun's magnetic field from the solar core to the corona and heliosphere, as well as the magnetic field's evolution on timescales from minutes to millennia.

The Sun's magnetic variability is thought to contribute to the global climate change through three mechanisms (Figure 1): (i) Variations in the total solar irradiance (TSI, integrated over all wavelengths ) can cause changes in the energy input into the Earth's atmosphere. We mention here that the near-UV, visible, and near-IR irradiance can directly affect the Earth's radiative balance and surface temperature. They constitute ≈ 99% of the Sun's total radiative output and penetrate the terrestrial atmosphere to the troposphere, reaching the surface; (ii) Variations of the solar UV irradiance, can alter chemical and physical processes in the Earth's upper atmosphere (stratospheric chemistry) . Changes in the stratosphere provide indirect climate effect, since the latter is coupled to the troposphere; (iii) Changes in low cloud cover can be induced by the solar cosmic ray flux reaching Earth, modulated by cyclic variations of the Sun's open magnetic flux (e.g. Marsh and Svensmark, 2000).

Solar irradiance is expected to follow the 11-year solar activity cycle. Krivova et al. 2009 for example have found that it varies by about 0.1% during the cycle. Almost 31% of the incident solar radiation is reflected back into space, 20% of which is absorbed by the lower atmosphere, and 49% is absorbed by the surface and oceans (Kiehl and Trenberth, 1997).

TSI measurements exist since 1978. They are in a 'patch-form' since they were taken with different instruments each with its own calibration, resulting in different scientific conclusions. The sunspot number is used as a proxy for the solar irradiance (e.g. Lean et al., 1995).

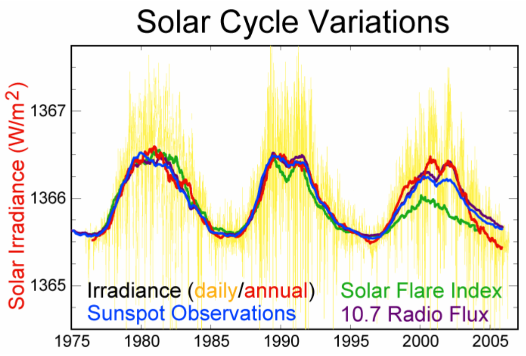


Figure 1. Monthly averages of different proxies of the solar magnetic activity. The color code describes the variables: Irradiance, sunspot number, radio flux at 10.7 cm indicating the UV-irradiance, solar activity in the form of flares. Data compiled from data taken from literature (e.g. Solanki and Krivova, 2003).

About 15 $Wm^{-2}$ (~1%) of the solar UV-radiation is absorbed by the terrestrial atmosphere. UV-radiation does not affect directly the climate as it is not supposed to reach the Earth's surface. Its effect is through the coupling of the stratosphere with the troposphere: UV radiation photo-dissociates molecular oxygen creating the ozone layer (Haigh et al. 2004). Ozone resides primarily in the stratosphere controlling the deposition of the solar energy in the stratosphere. Variations in the ozone amount alter the altitudinal temperature gradient from the troposphere to the stratosphere, and the latitudinal temperature gradient in the stratosphere from the equator to the poles.
UV irradiance changes by up to 10% in the 150–300 nm range and by an amount greater than 50% at shorter wavelengths, including the Ly-α emission line near 121.6 nm (e.g. Krivova et al. 2009 and references therein). It is more variable than TSI by an order of magnitude or so. It contributes significantly to the changes in TSI (15% of the TSI cycle, Lean et al., 1997). Krivova, and Solanki 2004 find that the average 11 year UV irradiance has a very similar form to the TSI between 1856 and 1999. However the relative change is greater for the UV irradiance.
There is a linear correlation between the annual mean irradiance and the radio flux of the Sun at 10.7 cm. Solar flares or coronal mass ejections, can trigger shock waves which leave signatures in radio spectrograms in the metric range (corona) up to the kilometric range (interplanetary medium) as they propagate in the solar corona or in the interplanetary medium. The F10.7 index is used as a proxy for the UV and EUV spectral irradiance, which varies day by day since it depends on the number of active regions on the Sun. This proxy shows the solar influence on terrestrial parameters such as the temperature at a given atmospheric layer. Radio data are taken daily since 1947. Mg II core-to-wing ratio obtained on-board of several spacecraft is also used as a proxy of UV irradiance (e.g. Viereck and Puga, 1999).
The third mechanism is affecting the terrestrial climate indirectly as well. Galactic cosmic ray (GCR) flux is suggested to affect tropospheric temperature via cloud-cover variations (low clouds have a strong cooling effect on climate). The physical mechanism is the following: GCR particles are essentially the source of ionization in the troposphere above 1 km. Changes in ionization affect the abundance of aerosols that serve as the nuclei of condensation for cloud formation. GCR flux varies inversely with solar activity. Reliable estimate of the evolution of the Sun's magnetic field, modulating cosmic rays, exist since 1868 (e.g. Solanki et al., 2000). This solar variable is measured directly with sufficient quality by Neutron Monitors since 1953. The data missing are reconstructed by converting the open magnetic flux and neutron monitor data into cosmic-ray flux. Krivova and Solanki, 2004 have found that the two quantities follow each other closely up to 1985, and diverge strongly after that.
Data interpretation indicates significant contribution of the solar variability to climate change is significant and that the temperature trend since 1980 can be large and upward on a time-scale of decades to centuries (e.g. Solanki and Fligge, 1999). Reconstruction models such as PCMOD and ACRIM (e.g. Lockwood 2008) estimate that the solar contribution to global warming is negligible since 1980. The Intergovernmental Panel for Climate Change (IPCC) 2007 claims that the solar contribution to climate change is negligible since 1950. However Scafetta (2009) suggested that IPCC 2007 could be using wrong solar data as well as models which underestimate several climate mechanisms. Taking into account the entire range of possible total solar irradiance (TSI) satellite composite since 1980, the author finds that the solar contribution to climate change ranges from a slight cooling to a significant warming, which can be as large as 65% of the total observed global warming.
Global temperature fall slightly after 1950 until the mid-1970s, and has risen sharply since, and particularly after 1985. This warming has been attributed to human activity by several authors (e.g., Mitchell et al., 2001). Solar irradiance seems to have decreased slightly in this period. A correlation between the cosmic-ray intensity and the coverage of low-lying clouds over a solar cycle has been suggested by Marsh and Svensmark (2000). Correlation between variations in solar irradiance and low cloud cover (affected through the atmospheric circulation) seems to be stronger than the correlation between galactic cosmic rays and low clouds. Kristjánsson et al., (2002) and (2004) demonstrated a large negative correlation between total solar irradiance and low cloud cover for the whole period 1983–1999, with no discrepancies after 1994. This implies that any positive correlation between GCR flux and low cloud cover would be coincidental. They argue that it is of no significance for the present global warming anyway, since solar irradiance appears to be almost constant over the last 50 years. Lockwood et al., (1999) assumed that GCR flux has decreased

significantly over the 20th century (i.e. the solar magnetic field increased) although the results were challenged by Richardson et al. (2002), who found no significant trends for either sunspots, GCR flux or the interplanetary magnetic field over the past 50 years. However positive trends in sunspot number and magnetic field do seem to exist. Marsh and Svensmark, (2000) suggested that GCR flux increase resulted in the decrease of low cloud cover by more than 8%, accounting for a significant fraction of the observed global warming.

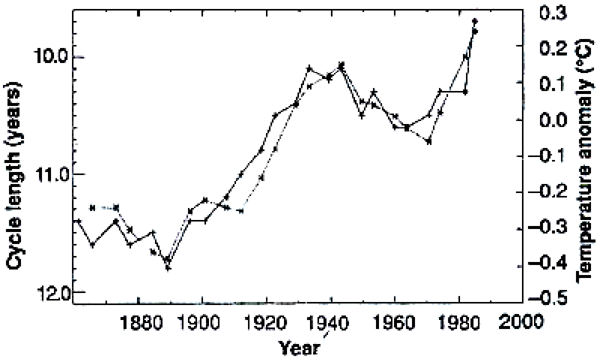


Figure 2. Land temperature of Northern Hemisphere (stars) and solar cycle length (inverted, pluses). Both time series are smoothed with a (1 2 2 2 1) filter weightings. Reproduction from Friis-Christensen and Lassen (1991) by Haigh, 2007.

To sum up the role that the Sun plays on the climate is being a subject of intense debate. Reconstruction models are based also on stellar observations, attempt to describe the past solar behavior on the terrestrial climate with contradicting results. Solar data suffer from bad quality in the past years (uncertainties in historical data of TSI for example) and of different instrument calibration in the satellite era. However there is a current need to distinguish between natural and anthropogenic causes of climate change. Therefore the study of the effect of the solar variability on the terrestrial climate is to the forefront of meteorological research. There is statistical evidence for solar influence on various meteorological parameters on all timescales (eg. see Fig. 2). However extracting the signal from the noise in a naturally highly variable system remains a key problem.
In the current research work we present preliminary results from the effect of the parameters of the solar activity on climate in Attica, Greece. We use several meteorological parameters from two weather stations based inside the city of Athens, Greece (New Philadelphia) and in the greater Athens in the north of Attica (Tatoi area). The solar variables studied are the TSI, UV-solar irradiance, cosmic ray flux and sunspot number, averaged over the 11-year solar cycle spanning the years from 1975 to 2000. The meteorological parameters are the temperature, atmospheric pressure, direction and force of wind, relative air humidity and precipitation. We use several statistical parameters as indicators of the climate change: the annually averaged value of each meteorological parameter; the error on the mean (standard deviation); the skewness; the kurtosis of the annual distribution of each of the above six meteorological parameters.

## 2. Methodology

Solar data span two 11- year solar cycles from 1975 up to 2005. The plot of all solar proxies is added for comparison at the end of every meteorological parameter graph. It is adapted from Solanki et al., 2006. The solar variables plotted are from top to bottom the TSI, F10.7 cm index as an indicator of the UV-irradiance, the magnitude solar flux, and the mean sunspot number. Not plotted here is the GCR flux, for which we remind the reader that this flux demonstrates an almost inversed behavior to the solar activity.
All meteorological data used in this work come from the Hellenic National Meteorological Service (EMY). Those data come from two stations on the Attiki area, one in Athens city (Nea Filadelfeia) and one in the northern of Athens (Tatoi area). The data cover 45 years from 1956 to 2001. For this work, as the solar data cover the period after 1975, the data covering the years 1956-1975 are ignored. Each station measures 6 meteorological parameters: temperature ($^{o}$C), atmospheric pressure (mm Hg), wind direction ($^{o}$, with $0^{o}$ to the north), wind force (knot), relative humidity (%) and precipitation (mm). For all data a point is measured every 3 hours (starting from midnight) except precipitation which is a 12 hours average. For all meteorological parameters the following statistical parameters are calculated for all years: average value, standard deviation, skewness and kurtosis (see Savvidou et al., these proceedings, for an explanation on these parameters).

## 3. Results and Discussion

### *3.1 Impact of solar activity on average annual values of meteorological parameters*

Figures 3-8 show from bottom to top the evolution of four solar parameters: mean sunspot number, magnetic flux, radio flux, and solar irradiance over time for the years 1975-2003. The four solar parameters show a cyclic variability with 3 maxima at about 1980, 1991 and 2002 and three minima at about 1975, 1986 and 1997.
Our simple analysis, although preliminary, does not suggest a correlation between the four solar parameters and the average annual values of the six meteorological parameters of the two stations in Athens area.

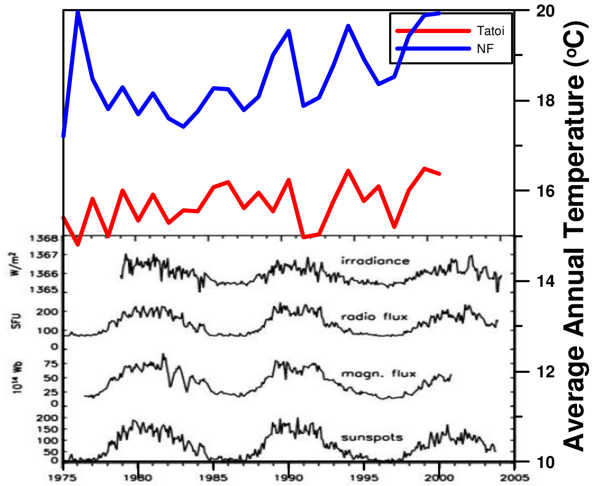


Figure 3. Average annual values of temperature for the two stations in Athens area and values of the four solar parameters studied here.

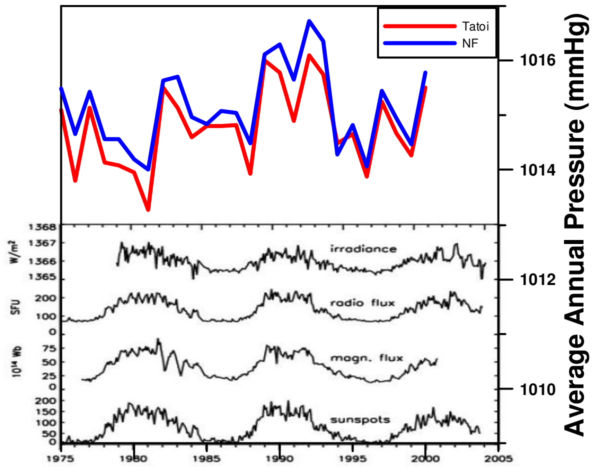


Figure 4. Average annual values of atmospheric pressure for the two statiosn in Athens area and of the four solar parameters studied here.

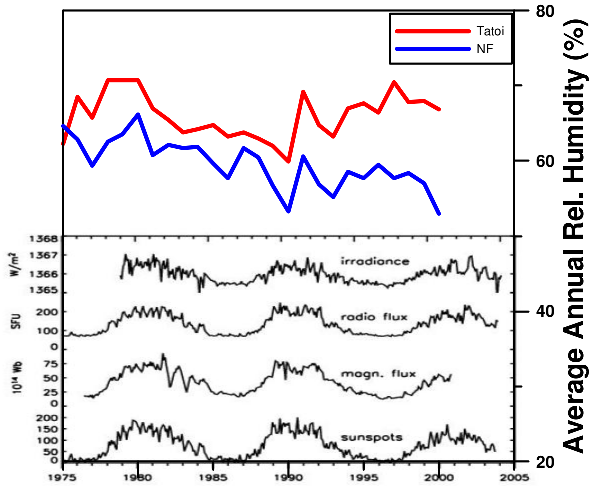


Figure 5. Average annual values of relative humidity for the two stations in Athens area and of the four solar parameters studied here.

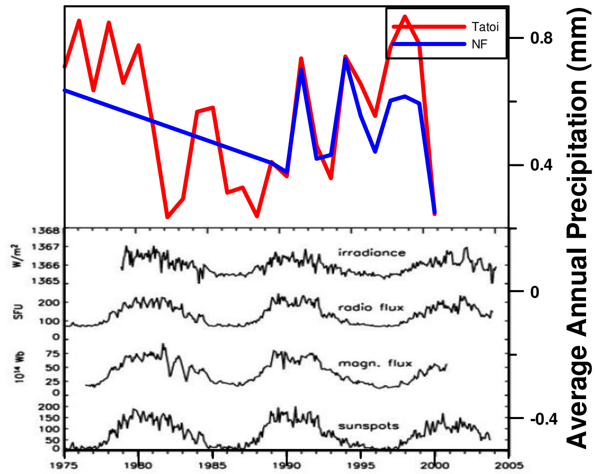


Figure 6. Average annual values of precipitation for the two stations in Athens area and values of the four solar parameters studied here.

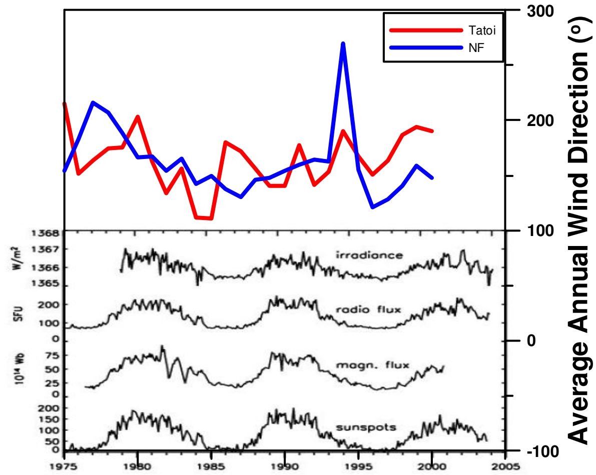


Figure 7. Average annual values of wind direction for the two stations in Athens area and of the four solar parameters studied here.

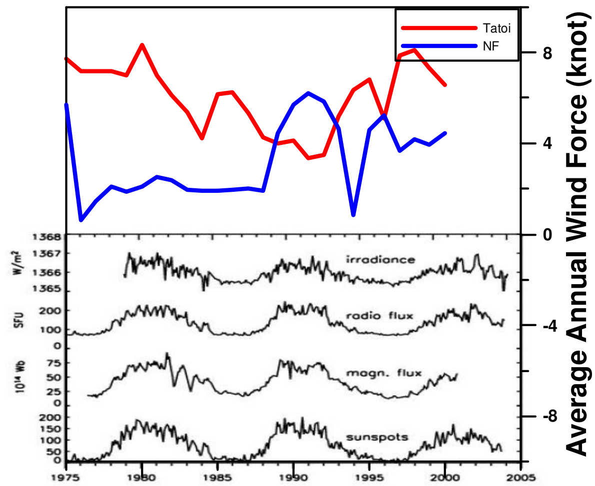


Figure 8. Average annual values of wind force for the two stations in Athens area and values of the four solar parameters studied here.

### *3.2 Impact of solar activity on annual standard deviation, skewness and kurtosis of meteorological parameters*

Current bibliography studies the impact of solar activity on global climate and data suggest a potential influence (eg. Haigh 2007). However results have been controversial. In the previous section we found that there is no obvious correlation between the four solar parameters and the average value of the six meteorological parameters in Athens area. The next step is to look if there is a correlation between the four solar parameters and the statistical characteristics of the six meteorological parameters. Figures 9-14 show the evolution of the four solar parameters in time and the standard deviation of the annual values of the six meteorological parameters; figures 15-20 the evolution of the same parameters and the skewness of annual data of the six parameters; figures 21-26 the same correlations using the kurtosis of the same data.

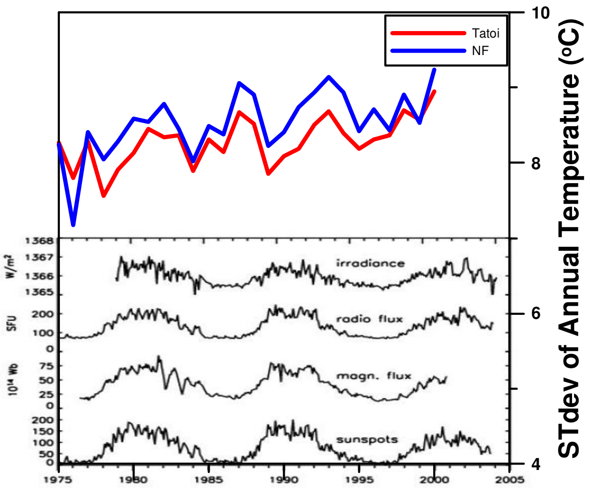


Figure 9. Average annual standard deviation of temperature for the two stations in Athens area and of the four solar parameters studied here.

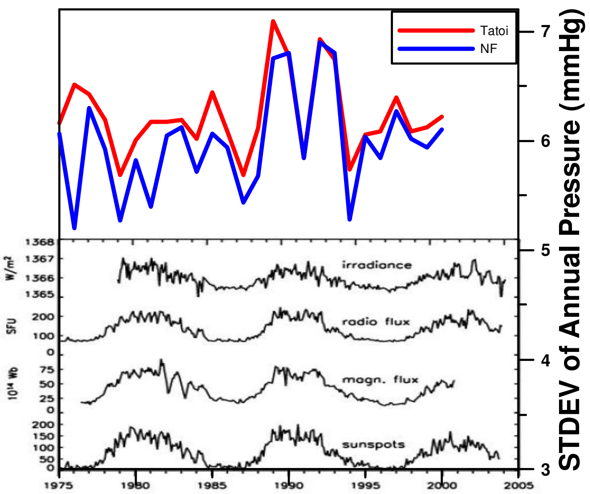


Figure 10. Average annual standard deviation of atmospheric pressure for the two stations in Athens area and values of the four solar parameters studied here.

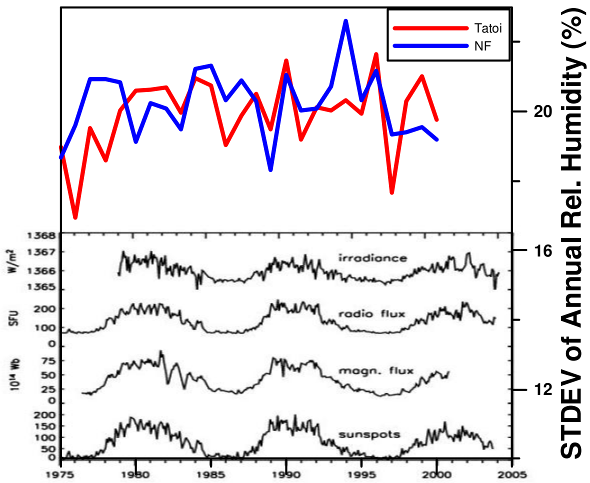


Figure 11. Average annual standard deviation of relative humidity for the two stations in Athens area and of the four solar parameters studied here.

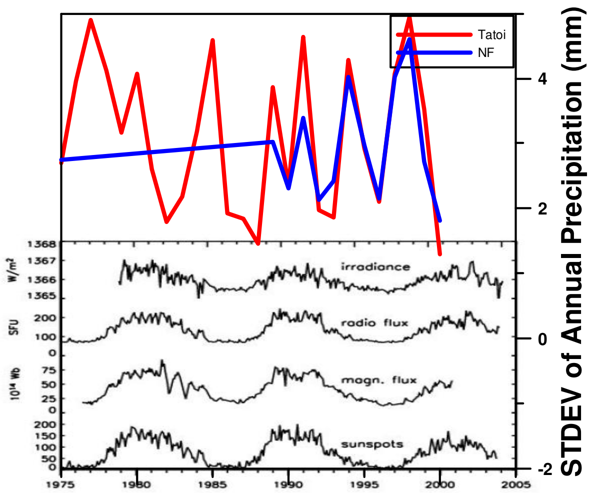


Figure 12. Average annual standard deviation of precipitation for the two stations in Athens area and values of the four solar parameters studied here.

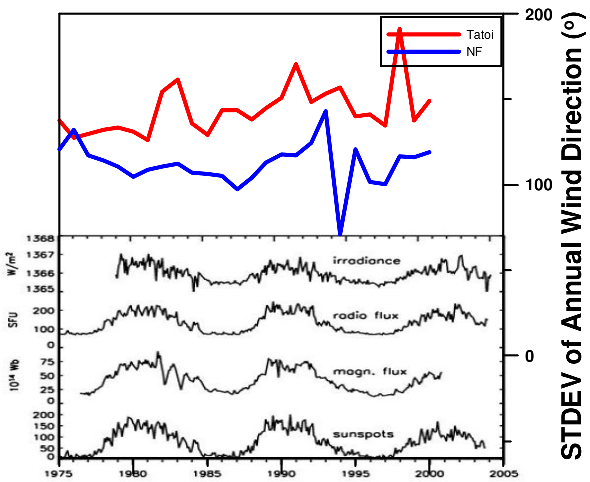

Figure 13. Average annual standard deviation of wind direction for the two stations in Athens area and of the four solar parameters studied here.

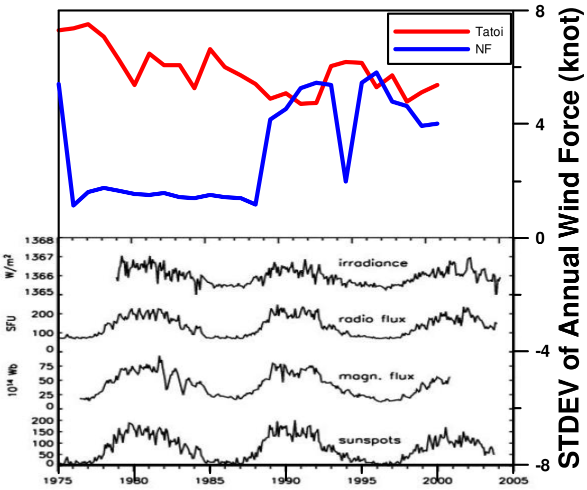


Figure 14. Average annual standard deviation of wind force for the two stations in Athens area and values of the four solar parameters studied here.

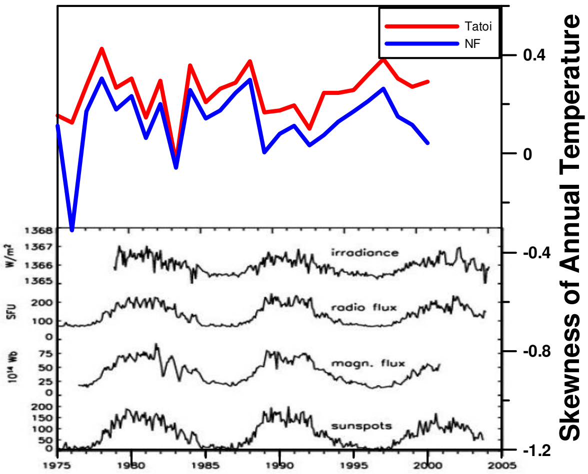


Figure 15. Annual skewness of temperature or the two stations in Athens area and of the four solar parameters studied here.

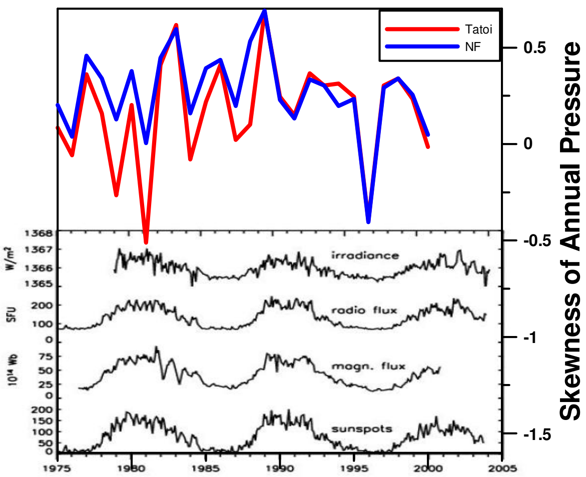


Figure 16. Annual skewness of atmospheric pressure for the two stations in Athens area and values of the four solar parameters studied here.

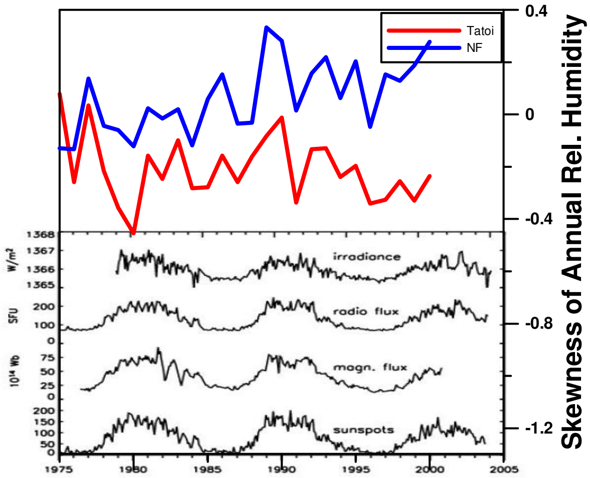


Figure 17. Annual skewness of relative humidity for the two stations in Athens area and of the four solar parameters studied here.

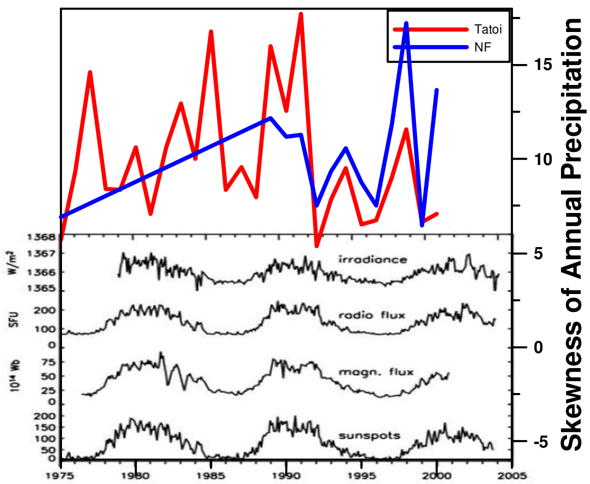


Figure 18. Annual skewness of precipitation for the two stations in Athens area and values of the four solar parameters studied here.

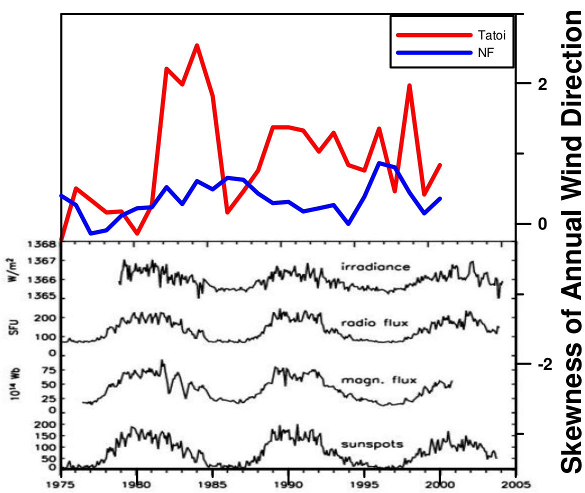

Figure 19. Annual skewness of wind direction for the two stations in Athens area and of the four solar parameters studied here.

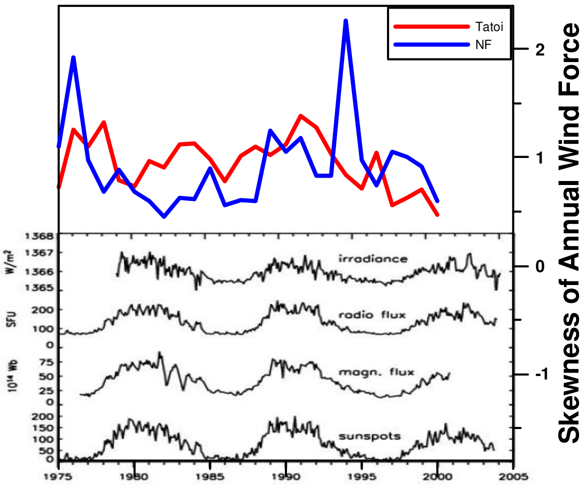


Figure 20. Annual skewness of wind force for the two stations in Athens area and of the four solar parameters studied here.

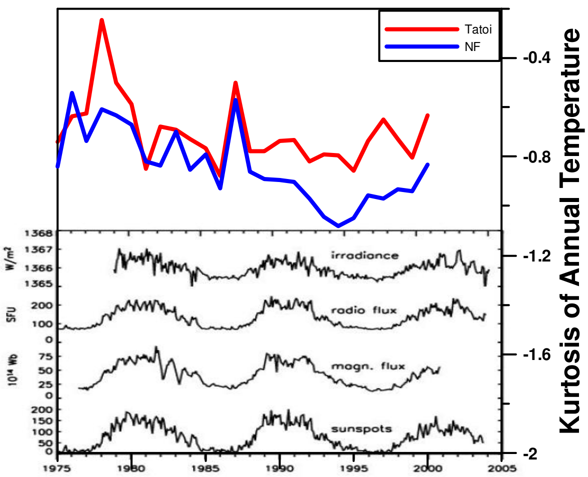


Figure 21. Annual kurtosis of temperature for the two stations in Athens area and of the four solar parameters studied here.

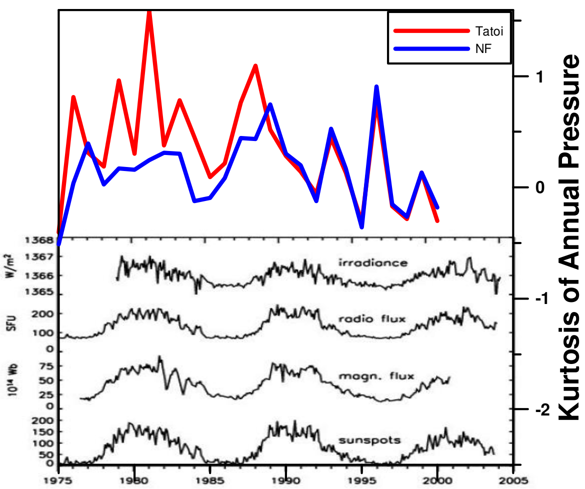


Figure 22. Annual kurtosis of atmospheric pressure for the two stations in Athens area and values of the four solar parameters studied here.

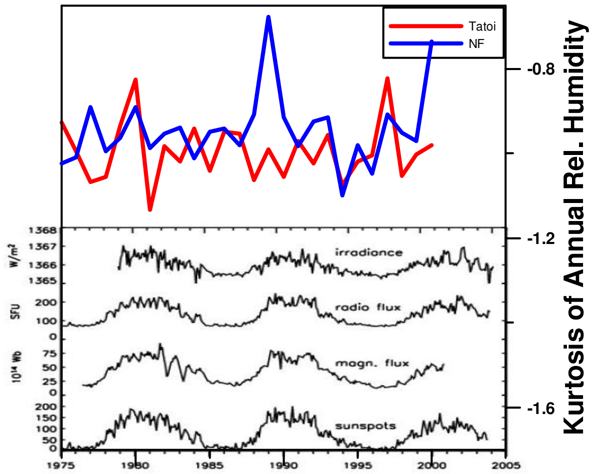


Figure 23. Annual kurtosis of relative humidity for the two stations in Athens area and of the four solar parameters studied here.

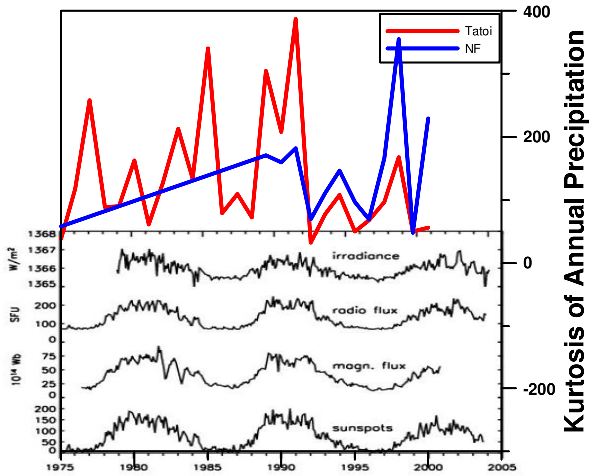


Figure 24. Annual kurtosis of precipitation for the two stations in Athens area and values of the four solar parameters studied here.

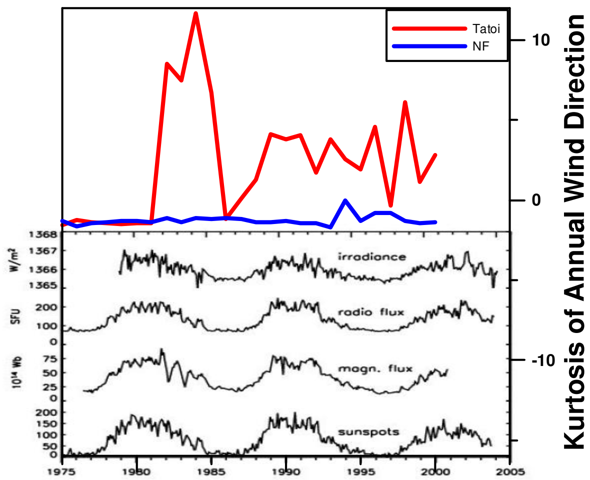

Figure 25. Annual kurtosis of wind direction for the two stations in Athens area and of the four solar parameters studied here.

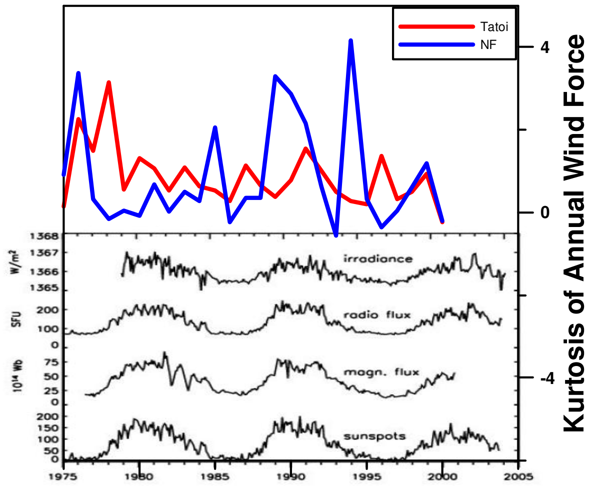


Figure 26. Annual kurtosis of wind force for the two stations in Athens area and of the four solar parameters studied here.

Similarly, as in the case of annual average values and solar proxies of solar activity are not correlated in an obvious manner. However, this is only a partial study, focused only in the greater Athens area. The correlations are probably altered due to urban and semi-urban conditions of the examined area.

Next step is to do a more sophisticated analysis which will include extracting the data from noise, use appropriate smoothing and simulating average temperature changes in Greece in response to climate forcings with for example an 1-D Energy Balance Model (EBM). We will also use more meteorological stations scattered all over Greece and the solar activity proxies TSI, UV-irradiance, F10.7 index, sunspot number, cosmic-ray flux/low cloud cover.

Another characteristic of meteorological data is the evolution of extreme values. The possible correlation of that characteristic with solar activity will also be examined.

**3. Conclusions**

In the current paper we present preliminary results of the effect that the solar variables-indicators of the solar activity have on climate characteristics in Attica, Greece.

The solar variables used were TSI, UV-solar irradiance, cosmic ray flux and sunspot number, averaged over two 11-year solar cycle spanning the years from 1975 to 2000. Meteorological parameters include temperature, atmospheric pressure, direction and force of wind, relative air humidity and precipitation data taken from two weather stations, one inside the city (Nea Filadelfeia) and one some kilometers outside the city, in the northern region of Attica (Tatoi).

Although Sun has the potential to affect climate we have found no particular trend between each set of parameters. However we suggest that this result is probably due to urban conditions. Our future work will include data from other stations in Greece (from the National Meteorological Service) from the north to the south (islands) together with analyzed solar variables (TSI, UV-irradiance, F10.7 index, sunspot number, cosmic-ray flux/low cloud cover).

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# Indicators of climate changes in the Athens area

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**Abstract:** The present work examines the variations of meteorological parameters in two stations in the greater Athens area in Greece, one station inside the city (Nea Filadelfeia) and one some kilometers outside the city, in the north of Attica (Tatoi). Sever meteorological parameters are analyzed in this work: temperature, atmospheric pressure, direction and intensity of wind, relative air humidity and precipitation. This work uses four statistical variables that could be used as indicators for climate changes. Those statistical variables are the average value, the standard deviation, the skewness and the kurtosis of the annual distribution of each of the above six meteorological parameter. The evolution of those statistical variables on the period 1956-2001 is analyzed.

**Keywords**: Climate changes, indicators, average temperature

## 1. Introduction

Climate is the long-term statistical expression of short-term weather. Climate can be defined qualitatively as "expected weather" (Bradley 1985), or quantitatively by statistical expressions such as central tendencies and variances. The overall distribution of climatological parameters, bounded by weather extremes, defines the climatic variability. Changes in climate can be defined by the differences between average conditions at two separate times. Climate may vary in different ways and over different time scales. Variations may be periodic (and hence predictable), quasi-periodic or non-periodic (Hare 1979).
Several meteorological parameters are used in studies of climate change scenarios. The bibliography about climate change is huge and shows the scientific interest about this topic (IPCC 2007).
Climate change will particularly affect the Mediterranean coast and southern European river basins, where there are many densely populated urban areas (Fischer and Schär 2010). The future changes in that region will lead to extended periods of high day and night-time temperatures, coupled with high humidity (Fischer and Schär 2010). The Intergovernmental Panel for Climate Change data (IPCC 2001) shows an increase in temperature over the 20th century of 0.6±0.2°C, with most of the warming occurring over the last 20 years (Ventura et al 2002).
Recently, the interest in the long-period tendencies of change (trends) of the whole range of values of meteorological variables, including the extreme ones, has arisen (Gruza and Rankova 2004). The question on whether the observed climate of the Earth is becoming more variable and more extreme is one of the key ones in review reports of the Intergovernmental Panel on Climate Change (IPCC 2007).
A lot of indicators have been used to quantify climate change. Some of them are based on the extent of some consequence of climate changes. Alison Donnelly et al. (2004) conclude that for the last thirty years the meteorological data shows a clearly climate change and they separate the indicators into five sectors: agriculture, plant and animal distribution patterns, phenology, palaeoecology and human health. Novotny and Stefan (2007) use as an indicator the flow of water streams in Minnesota. Molnia (2006) proposes as indicator the evolution of glaciers in Alaska as he studies their action by the end of 19 century until the beginning of 21 century.
Other indicators are the evolution of meteorological parameters such as temperature or humidity. Giannakopoulos et al. (2010) use daily rainfall data and maximum, minimum and mean temperature data to calculate and compare extremes data of temperature and rainfall for Cyprus for the past (1961-1990) and estimate some future values (2071-2100).
Gruza et al. (1999) use temperature and precipitation data to estimate some indicators such as mean value, min and max values, standard deviation, linear trend coefficient and the percentage of total variance explained by the linear trend. Also, they use as an indicator for the extremes the total days, for the winter and summer, where daily temperature and rainfall are higher or lower than some limits.
Pal and Tabbaa (2009) study the precipitation in Kerala, India, and use some indicators, such as total precipitation from wet days, total number of dry days, total precipitation from > 95$^{th}$ and > 99$^{th}$ percentile of the wet days, max precipitation in 1 day, maximum precipitation in five consecutive days, extreme frequency, i.e. number of days with rainfall >95 percentile in the season days and extreme percent, i.e. proportion of total seasonal rainfall from all events above the average long-term 95th percentile.

The objective of current study is to examine the variations of meteorological parameters in Greece, in order to propose suitable indicators for climate changes. This work is more particularly focused on two stations in the greater Athens area, one station inside the city (Nea Filadelfeia) and one some kilometers outside the city, in the northern region of Attica (Tatoi). Six meteorological parameters are studied in this work: temperature, atmospheric pressure, direction and force of wind, relative air humidity and precipitation. The target is to find out some indicators and explain the variations of meteorological data using four statistical parameters: the average value, the standard deviation, the skewness and the kurtosis of the annual distribution of each of the above six meteorological parameter.

## 2. Methodology used

The data used in this work come from the Hellenic National Meteorological Service (EMY). Those data come from two stations on the Attiki area, one in Athens city (Nea Filadelfeia) and one in the northern of Athens (Tatoi). The data cover 45 years from 1956 to 2001. Each station measures 6 meteorological parameters: temperature ($^oC$), atmospheric pressure (mm Hg), wind direction ($^o$, with $0^o$ to the north), wind force (knot), relative humidity (%) and precipitation (mm). For all data a point is measured every 3 hours (starting from midnight) except precipitation which is a 12 hours average. For all meteorological parameters the following statistical parameters are calculated for all years: average value, standard deviation, skewness and kurtosis. Those statistical parameters are defined as:

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \quad (1)$$

$$s = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{(n-1)}} \quad (2)$$

$$Skewness = \frac{n}{(n-1)(n-2)}\sum_{i=1}^{n}\left(\frac{x_i - \bar{x}}{s}\right)^3 \quad (3)$$

$$Kurtosis = \left\{\frac{n(n+1)}{(n-1)(n-2)(n-3)}\sum_{i=1}^{n}\left(\frac{x_i - \bar{x}}{s}\right)^4\right\} - \frac{3(n-1)^2}{(n-2)(n-3)} \quad (4)$$

The physical meaning of those parameters is shown in figures 1, 2 and 3.

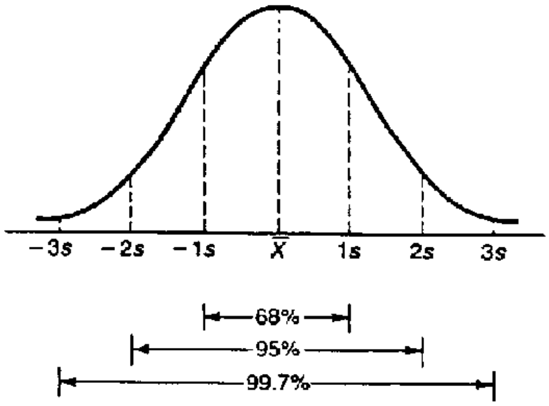


Figure 1. The mean value and the standard deviation (s) of the normal distribution

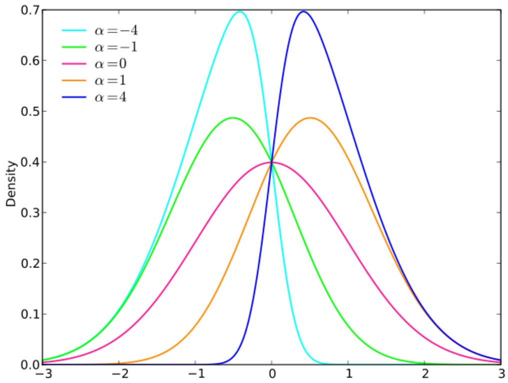


Figure 2. Symmetrical and skewed distributions

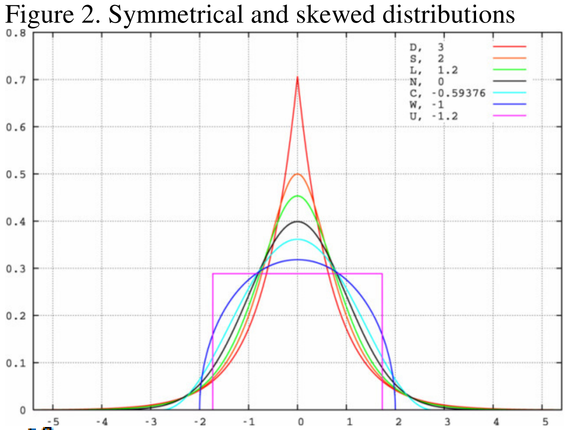


Figure 3. Kurtosis of some distributions.

## 3. Results and discussion

### *3.1 Temperature*

Figure 4 shows the average temperature of the two stations. Tatoi shows a slight decrease until 1975, followed by a constant slight increase. Nea Filadeldfeia shows a constant increase caused by the change of micro-climatic conditions due to the city expansion.

Figure 5 shows the annual temperature standard deviation of the two stations. The standard deviation is around 7.5-9.5$^oC$ with an increased trend, indicating that not only there is an increase of average temperature, but also an increase of temperature variability. The curves of both stations have the same shape, but Nea Filadelfaia has higher standard

deviation comparing to Tatoi, and this difference increases with time.
For both stations, annual skewness of temperature has the same shape and is slightly positive (figure 6), indicating that the "tail" of temperature is most at the right side (higher temperatures) than at the left side (lower temperatures) of the temperature distribution. This means that the cases of extreme high temperatures increase with time.
Annual kurtosis of temperature is slightly negative (figure 7), indicating that the temperature distribution is quite flat indicating that there is quite large distribution of temperature and not only around the average annual value. This flatness increases with time, especially in the case of Nea Filadelfeia, due to urban conditions.

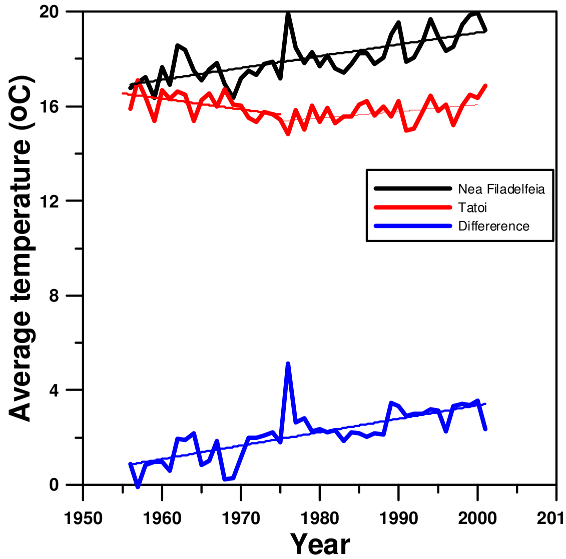


Figure 4. Average annual temperature of the two stations in Athens area and difference of the two values.

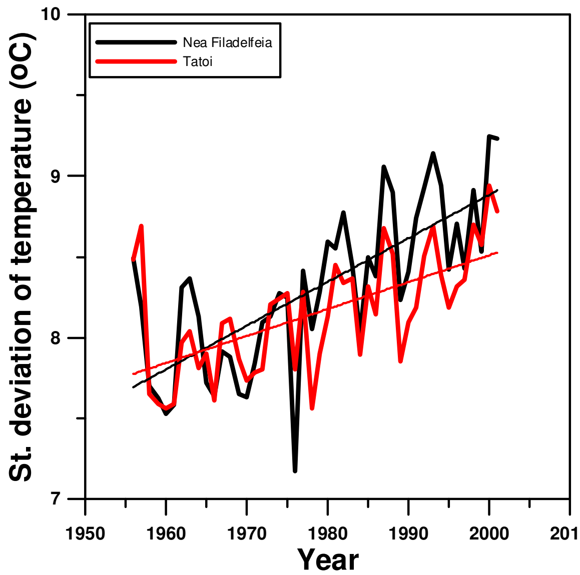


Figure 5. Annual standard deviation of temperature of the two stations in Athens area.

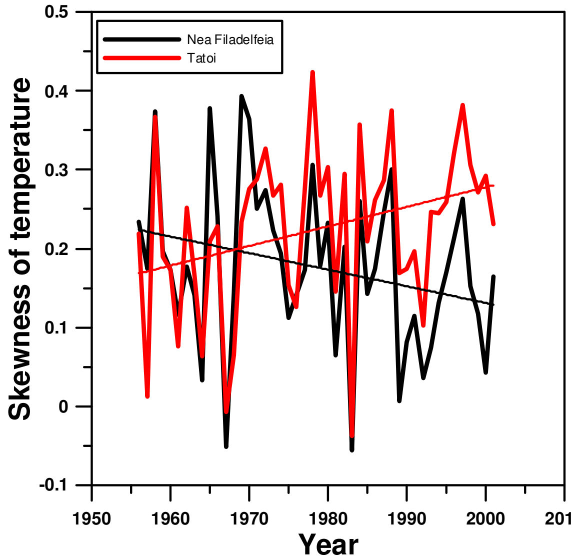


Figure 6. Annual skewness of temperature of the two stations in Athens area.

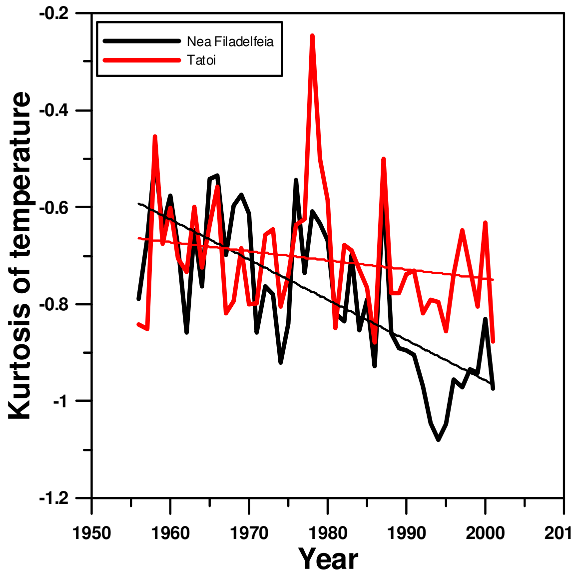


Figure 7. Annual kurtosis of temperature of the two stations in Athens area.

### *3.2 Atmospheric pressure*

Annual average pressure has the same shape for both stations (figure 8), with Nea Filadelfeia having slightly higher values due to urban conditions. A very slight decrease is observed until 1980 and quite constant values after that year.
Standard deviation of pressure is about 5-7 mm Hg and increases with time (figure 9), indicating that, as in the case of temperature, the variability of atmospheric pressure increases with time. Both stations have very similar shape, with Nea Filadelfeia having lower variability due to urban conditions (contrary to the variability of temperature, where Nea Filadelfeia has higher variability than Tatoi).
Annual skewness is very similar for both stations, slightly positive and increases with time (figure 10), indicating that, as in the case of temperature, the tail of the pressure distribution is at the right of the pressure distribution and that trend slightly increases with time.

Annual kurtosis is also very similar for both stations, slightly positive and decreases with time (figure 11), indicating that pressure distribution, contrary to temperature distribution is quite sharp around the average value, but this trend decreases with time.
It must be noticed that for all four parameters examined here, the difference between the two stations are not so significant in the case of atmospheric pressure as in the case of temperature.

### *3.3 Wind direction*

The average wind direction in Tatoi shows a general decrease from 160-240$^o$ (roughly south to south-west) to 120$^o$ (south-east) until 1985 and a constant increase to about 220$^o$ (roughly south-west) after that year (figure 11). Wind direction of Nea Filadelfeia has a particular trend: an increase from 120$^o$ to 200$^o$ (1956-1980), a decrease until 1986,, an increase until 1995, a sharp decrease for two years and an again an increase.

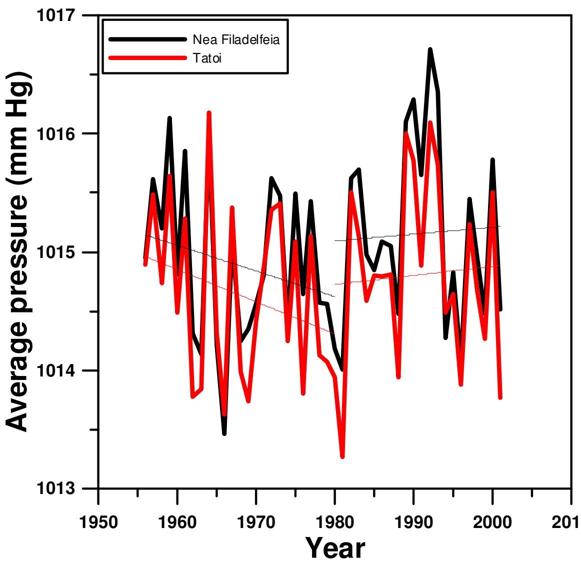

Figure 8. Average annual pressure of the two stations in Athens area.

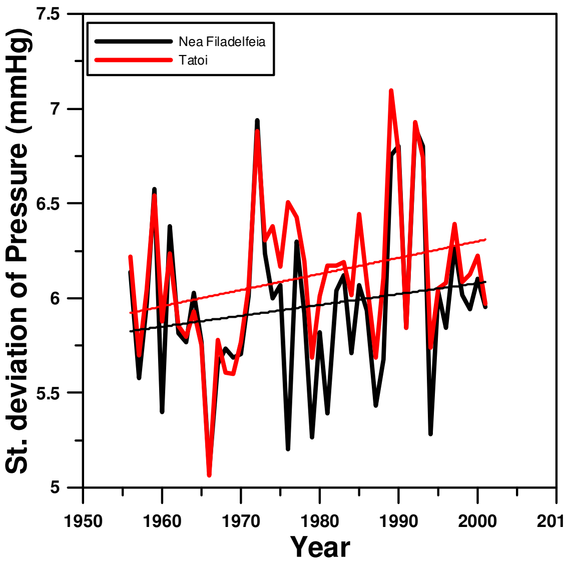

Figure 9. Annual standard deviation of pressure of the two stations in Athens area.

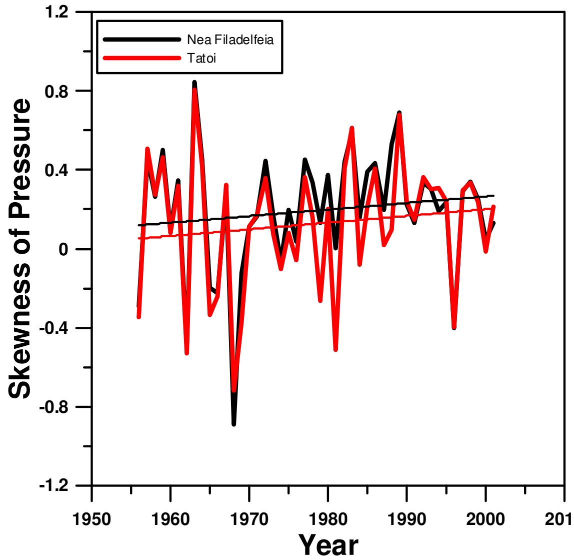

Figure 10. Annual skewness of pressure of the two stations in Athens area.

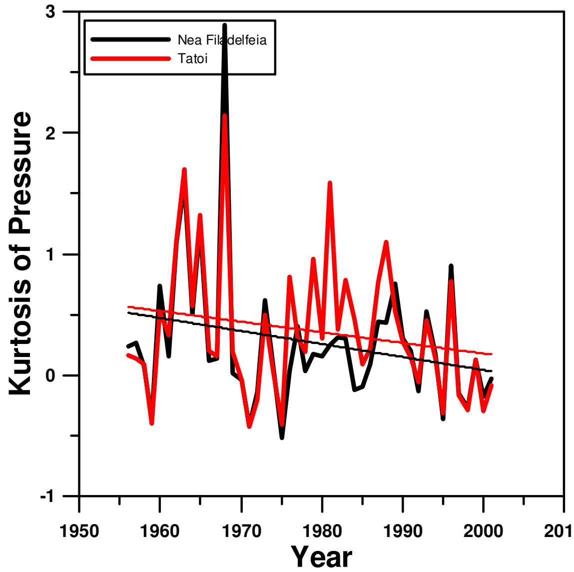

Figure 11. Annual kurtosis of pressure of the two stations in Athens area.

Of course, the two stations have very different curves due to the local relief especially Parthina mountain. However, these results show that urban conditions contribute to have a very unstable wind direction over time.
Standard deviation of wind direction is very high from 80 to over 180$^o$ (figure 12) indicating the significant variability of this parameter. Tatoi has a general increased trend of standard deviation, especially afte 1976. The standard deviation of Nea Filadelfeia increases until the same date and remains quite constant.
Skewness of wind direction is higher than zero and very different for the two stations after 1975-1980 (figure 13). Generally, skewness decreases with time until 1980 for both stations. After that year, it remains quite constant at Nea Fialdelfeia and shows a very sharp increase at Tatoi followed by a constant decrease.
Kurtosis is very close to zero until 1980 (figure 14), indicating that the wind direction distribution is very similar to the normal distribution. After 1980, kurtosis

of Nea Fialdelfeia slightly increases, but the increase observed in the case of Tatoi is very high, indicating that the wind direction distribution is very sharp around the mean value after this year in that station.

### *3.4 Wind force*

Wind force at Tatoi station has a slight increase until about 1980 and then, after a shift down for a few years, a new increase (figure 15). Globally, one could say that wind force remains constant within the limits of 4-8 knots. Nea Fialdelfeia has a particular trend with very low wind force from 1975 to 1990.
Standard deviation of wind force is very high and similar to the average values (figure 16). Standard deviation of wind force shows a constant decrease, indicating that the variability in this meteorological parameter decreases with time.

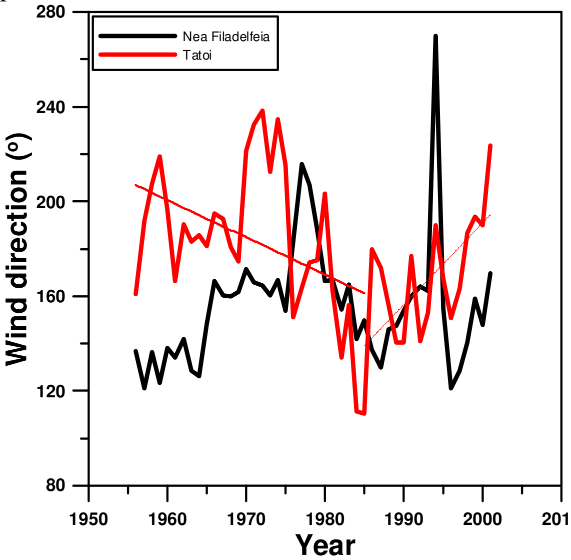


Figure 12. Average annual wind direction of the two stations in Athens area. 0° corresponds to north.

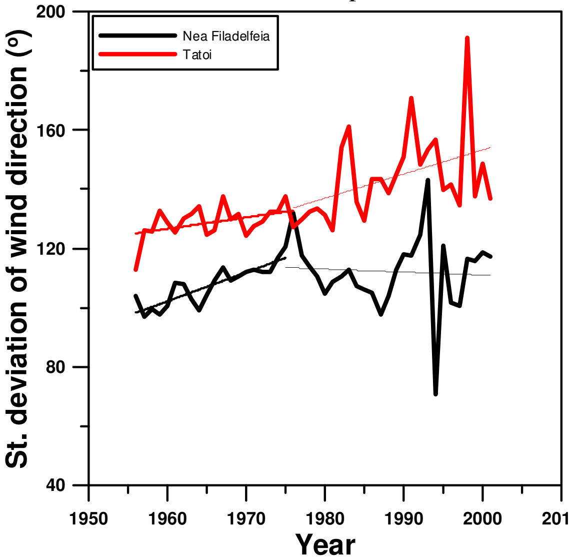


Figure 12. Annual standard deviation of wind direction of the two stations in Athens area.

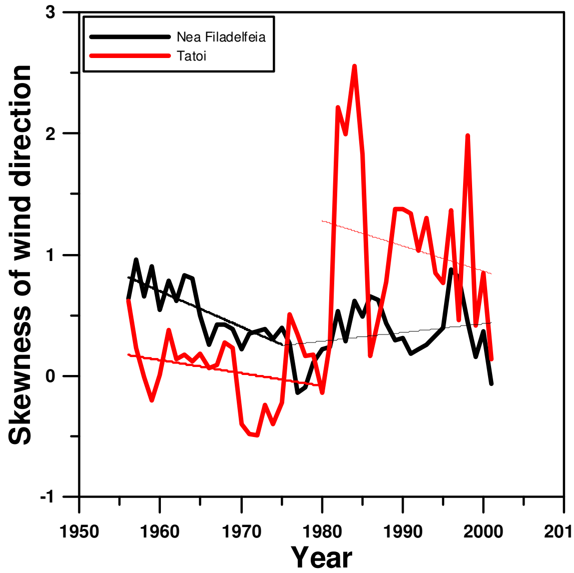


Figure 13. Annual skewness of wind direction of the two stations in Athens area.

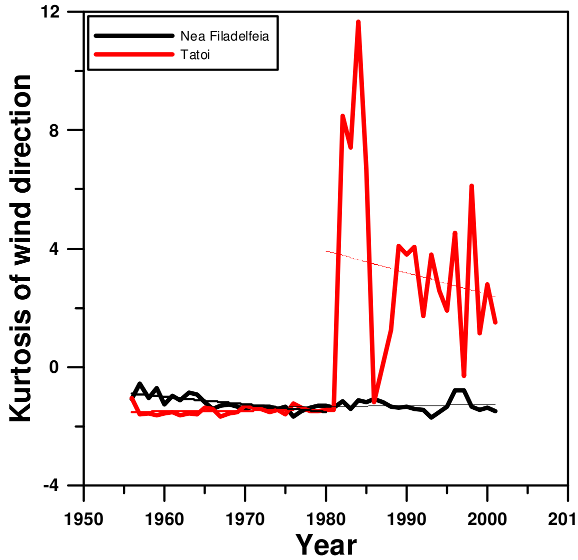


Figure 14. Annual kurtosis of wind direction of the two stations in Athens area.

Skewness of wind force is positive, indicating that the tail of wind force distribution is found on the right of the distribution (figure 17). The skewness of Tatoi shows a significant decrease, indicating that the very high values of wind force diminishes with time. The skewness of Nea Filadelfeia also decreases but with a very low slope.
Wind force kurtosis of Nea Filadelfeia is very close to zero indicating that this parameter has a distribution very close to the normal one (figure 18). However, there is a slight increase with time. Kurtosis of Tatoi is positive the early years of our study but decreases with time to approach the values of Nea Filadelfeia.

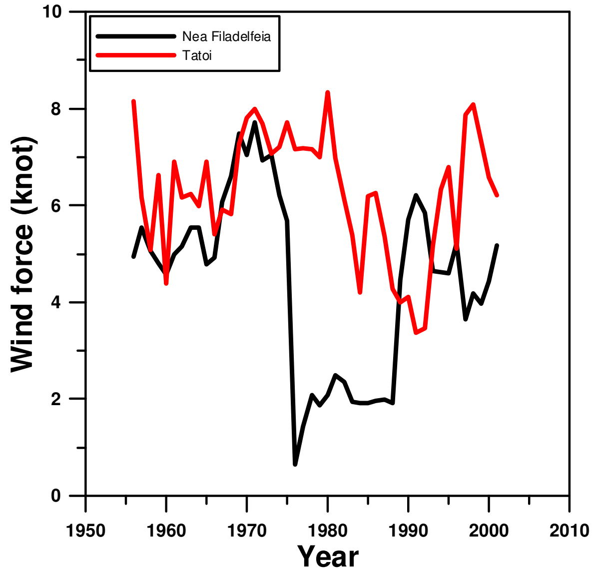


Figure 15. Average annual wind force of the two stations in Athens area.

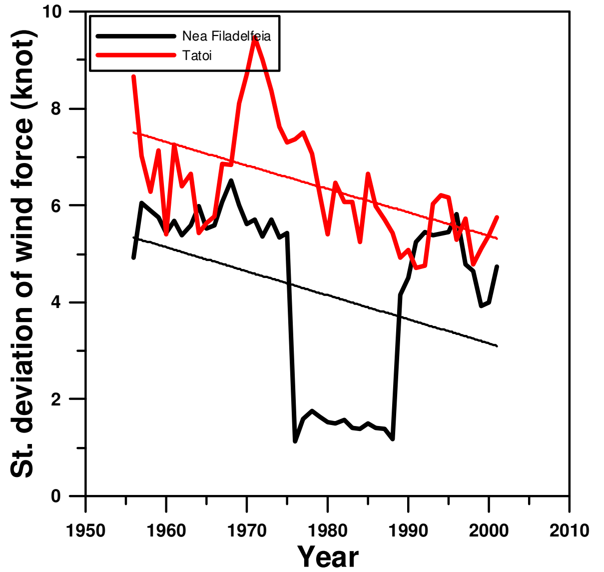


Figure 16. Annual standard deviation of wind force of the two stations in Athens area.

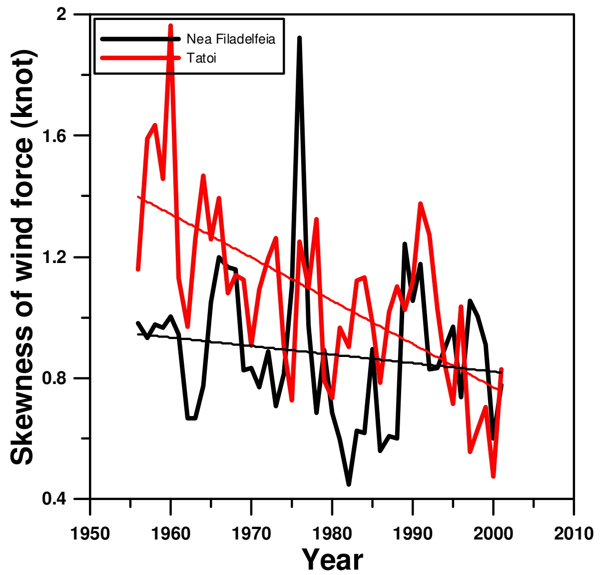


Figure 17. Annual skewness of wind force of the two stations in Athens area.

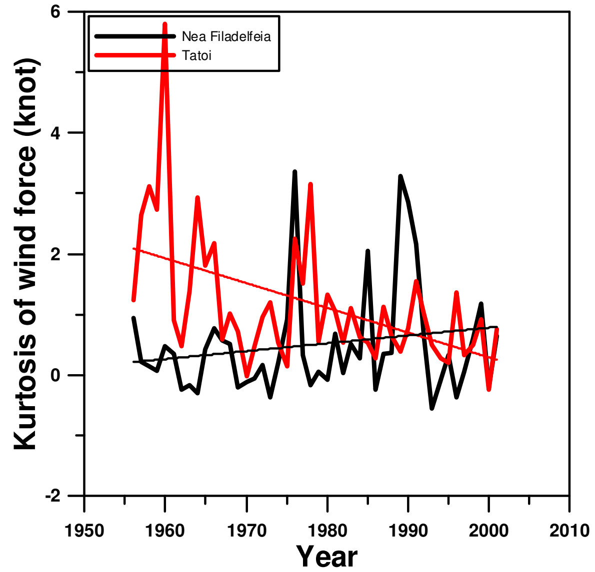


Figure 18. Annual kurtosis of wind force of the two stations in Athens area.

### *3.5 Relative humidity*

Average annual relative humidity increases slightly at Tatoi, but decreases significantly at Nea Filadelfeia (figure 19), due to the increase of urban conditions.
Standard deviation of relative humidity corresponds to about 30-40% of average values (figure 20) and increases slightly with time in the case of Tatoi. Nea Filadelfeia has a sharp increase during the first years to follow Tatoi trend after 1975. That statement indicates that the humidity variability generally increases with time.
Annual skewness of relative humidity is slightly negative until 1975, indicating that the tail is on the left of the humidity distribution (figure 21). Skewness of Tatoi remains quite constant during the years studied. After 1975, skewness of Nea Filadelfeia increases constantly and becomes positive, indicating that the tail of the humidity distribution is now more and more on the right.

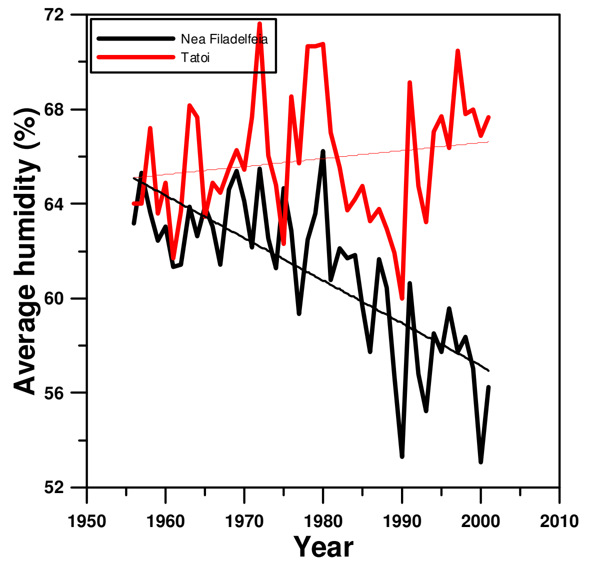


Figure 19. Average annual relative humidity of the two stations in Athens area.

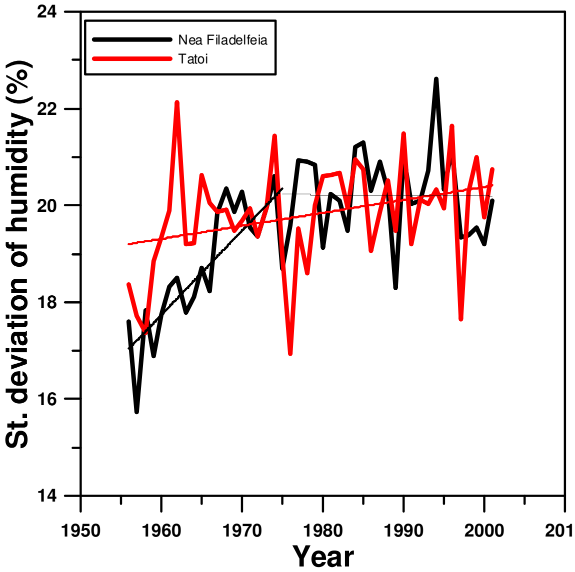


Figure 20. Annual standard deviation of relative humidity of the two stations in Athens area.

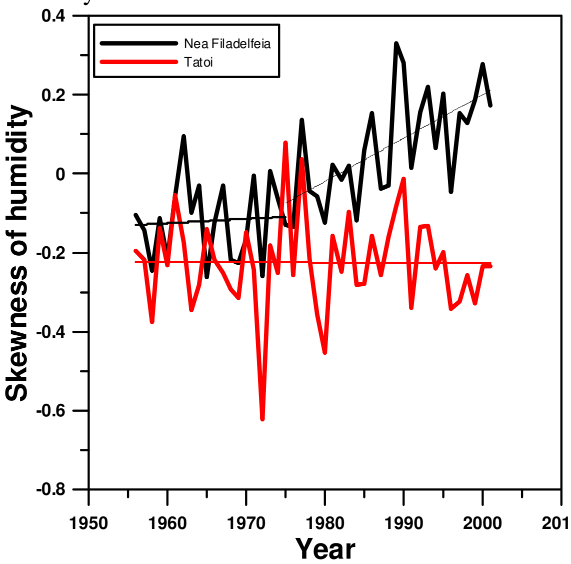


Figure 21. Annual skewness of relative humidity of the two stations in Athens area.

Kurtosis of both stations has a quite constant trend over the years studied and remains negative (figure 23), indicating that humidity distribution is quite flat.

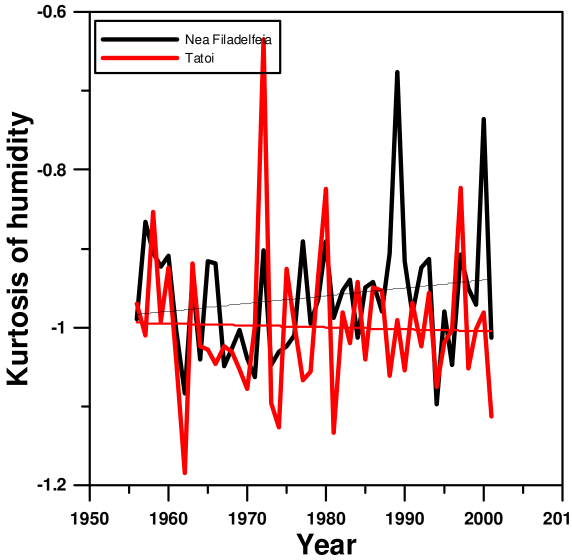


Figure 22. Annual kurtosis of relative humidity of the two stations in Athens area.

### *3.6 Precipitation*

Precipitation data is missing for Nea Filadelfeia from 1976 to 1988. For both stations precipitation shows a general increase until 1980 and after a shift down, a new general increase is observed after 1990 (figure 23). There is not significant differences between the two stations.

Standard deviation of precipitation is very significant as it corresponds to about 1.5 times the average value (figure 24), indicating that the variability of this parameter is very high. However, the trend of standard deviation is quite constant with time indicating that the variability of this parameter general remains constant over time.

Skewness of precipitation is very positive, indicating that the tail of the distribution is on the right (figure 25). Both stations have very similar curves and skewness trend is constant with time.

Kurtosis of precipitation is very high for both stations (figure 26), indicating that the precipitation distribution is very flat. As in the case of skewness, kurtosis trend is quite constant with time for both stations.

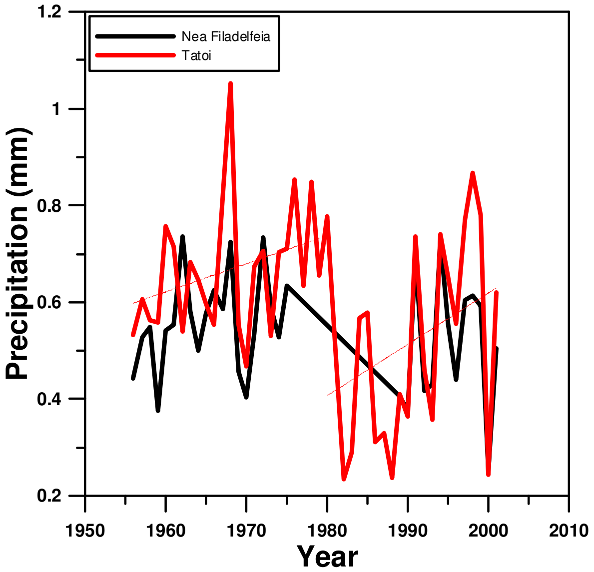


Figure 23. Average annual precipitation of the two stations in Athens area.

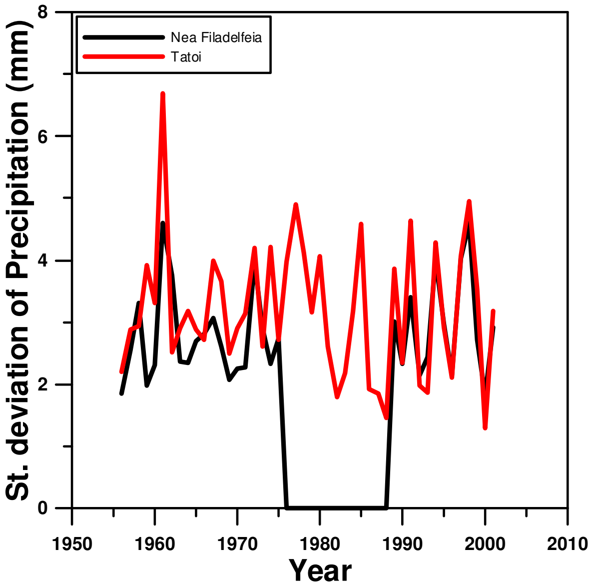


Figure 24. Annual standard deviation of precipitation of the two stations in Athens area.

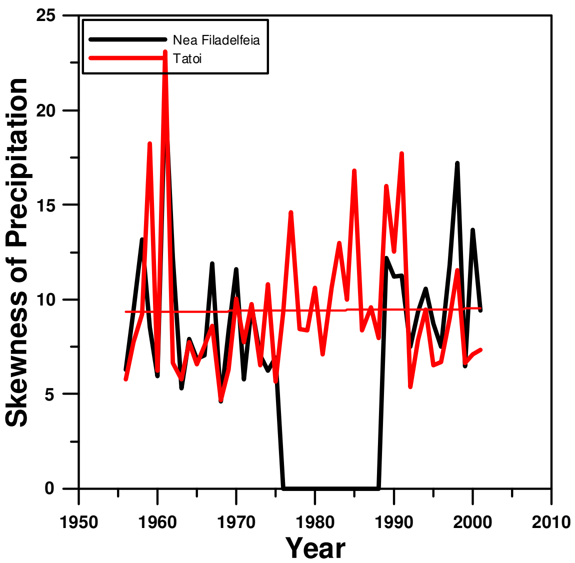


Figure 25. Annual skewness of precipitation of the two stations in Athens area.

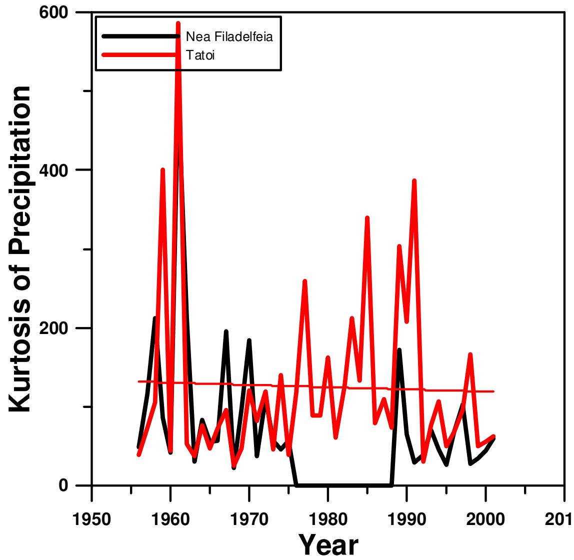


Figure 26. Annual kurtosis of precipitation of the two stations in Athens area.

### 4. Conclusions

Average temperature increases in both stations after 1975, while that of Nea Filadelfeia increases from 1956 due to the expansion of the city. The average temperature of Nea Filadelfeia is higher than that of Tatoi due to urban conditions. The variability of temperature also increases during those years. Annual skewness is slightly positive, indicating that the “tail” of temperature is found at the area of higher temperatures and the cases of extreme high temperatures increase with time. Annual kurtosis is slightly negative, indicating that there is quite large distribution of temperature.

Nea Filadelfeia has slightly higher values of atmospheric pressure than Tatoi due to urban conditions. There is no significant change of that parameter over time. The variability of atmospheric pressure increases with time. Annual skewness is slightly positive and increases with time indicating that the tail of the pressure distribution is shifted more and more to the right of the pressure distribution. Annual kurtosis is also slightly positive and decreases with time, indicating that pressure distribution is quite sharp around the average value, but this trend decreases with time.

Wind direction is very different at the two stations due to urban and geographical conditions. The average annual wind direction of both stations shows significant changes over time and has a high variability. Skewness and kurtosis of wind direction also have several changes over time. Skewness is generally higher than zero and kurtosis very close to zero until 1980 but increases after that year.

The average annual wind force of both stations shows significant changes over time and has a high variability; however, the variability decreases over time. Skewness of wind force is positive, indicating that the tail of wind force distribution is found on the right of the distribution. The general trend is decreasing indicating that the very high values of wind force diminish with time. Wind force kurtosis is quite close to zero indicating that this parameter has a distribution very close to the normal one. However, there is a slight increase with time.

There is a significant difference in relative humidity of the two stations due to urban conditions. Average annual relative humidity increases slightly at Tatoi, but decreases significantly at Nea Filadelfeia. The variability of this parameter is quite high and increases with time. Annual skewness is slightly negative until 1975, indicating that the tail is on the left of the humidity distribution. Skewness of Tatoi remains quite constant. After 1975, skewness of Nea Filadelfeia increases constantly and becomes positive. Kurtosis of both stations has a quite constant trend and remains negative, indicating that humidity distribution is quite flat.

Precipitation shows a general increase until 1980 and after a shift down, a new general increase is observed after 1990. The variability of this parameter is very high but general remains constant over time. Skewness of precipitation has a constant trend over time and is very positive, indicating that the tail of the distribution is on the right. Kurtosis trend is also constant with time and is very high indicating that the precipitation distribution is very flat.

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# Statistical estimations in climate and environmental changes; utilization of alternative energy sources for better climate management

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**Abstract**: The global warming phenomenon, the effect of greenhouse gases and the accompanied climate and environmental changes are discussed and analyzed. Their biological, economical, and societal impact on our life and the planet's life have to be considered carefully [2,5]. Solutions, regulations and ideas are proposed. Statistical methods are presented based on specific tests and verified by measured data. New technologies that incorporate alternative energy resources can contribute to minimize the greenhouse emissions and the energy demand [8]. Such technologies can be considered the fuel cells and solar membrane reactors [6,7]. Involved optimization techniques have employed appropriate models to manage the critical environmental conditions. Statistical figures and modeling results are presented to show the effects of the climate and environmental changes. Comparable tables are also used to show characteristic increases in several important parameters. The goal of the new millennium is zero or near zero emissions. Taking into account several political, economic, ecological and cultural initiatives more and more people are stepping in to work towards zero emissions technologies or technologies with objectives the de-carbonizing energy production and consumption. New technologies such as fuel cells, hydrogen systems, and renewable energy utilization can contribute to the desired environment. Useful policy actions to achieve this goal of zero emissions can consider the Kyoto Protocol, Carbon Markets and Process Flexibility Mechanisms. Although tremendous investments in climate science have helped using new monitoring systems in the oceans and space, employing state-of-art computers, taking advantage of several of experts internationally, our understanding is still incomplete. Researchers are going to observe, analyze, debate and redefine more accurately these areas of understanding in the coming days.

**Keywords:** climate changes, greenhouse effects, Kyoto protocol, membrane reactors, hydrogen energy technologies, fuel cells.

## 1. Introduction

The incoming phenomenon of global warming, the effect of greenhouse gases and the accompanied climate/environmental changes have to be watched, monitored, and discussed based on the observed data collected and analyzed.

Changes in several parameters such as earth-surface and sea temperature, $CO_2$ emissions and earth concentration, sea level and other conditions have to be presented and analyzed. Their biological, environmental, and economical impact on our life and planet's life are the core subjects which have to be considered carefully from an analysis and scientific point of view.

Solutions, regulations and ideas are significant to be proposed and followed. New, updated environmental treaties and regulations must be adopted and followed to solve and diminish such problems as global warming, deforestation, pollution increase, toxic substances release, and waste-garbage disposal. Environmental technologies accompanied by green chemistry principles must be implemented including new energy-efficiency and renewable energy technologies. In this paper we will choose as such new energy technology the fuel cell technology.

Today's and future's desired technical targets all focus at zero or near zero carbonaceous emissions in the industrial, stationary, and transportation sources in order to minimize and stabilize the emitted $CO_2$ concentrations which already are concentrated at alarming proportions within the atmosphere and earth systems. The so-called "greenhouse gases effect" coming from increased carbon dioxide and methane concentrations, projects negative weather patterns and negative environmental changes in earth, sea, and oceanic ecosystems.

Even if it is possible to stop drastically the $CO_2$ emissions by technical means including fuel cells and modern (zero or near zero emissions) power installations, we are still committed to some degree of warming in the incoming decades based on current trends. There is a better view now about the actual climate changes and their actual effects in the planet earth for the next 30 to 40 years. It is going to take a concerted effort to stabilize and even reduce currently measured greenhouse effects. Unless major environmental changes occur, it seems that global warming trends will continue with possible projected detrimental effects for arctic, mountainous, and coastal areas.

There are more recent readily observed changes in the climate. We observe more intense storms and heavier local rainfalls. We also observe not smaller, but rather bigger climate changes as time passes. Warmer air streams are translated into warmer oceans easily, and warm oceans emanate the jet fuel that directs and drives predominantly the hurricanes water turbines.

Moreover, the ocean surface temperatures worldwide have risen more than $1^oF$, since the 1970's, according to several measurements. This observed sea temperature increase matches the global air temperature which has

also increased a degree according to recent measurements. The hottest years ever observed, as measured by average temperature readings are in the following series: 1998, 2002, 2003, 2001, 1997. It has to be verified with continuous and accurate measurements and with systematic analysis of local sensitive spots of earth, oceanic, and atmospheric places, whether the current fossil based fuel conversion and utilization (e.g., coal, oil and gas) are totally responsible for these effects and in what degree
[4,10]. Measured changes (deviations) in the global ocean surface temperature from the baseline (which is the average surface temperature from the 1880-2005 years) show the following numbers in degrees $^{o}$C:

**Table 1: Changes in global ocean surface temperature from the baseline,**

| Years: | Temperature Change ,$^{o}$C: |
|---|---|
| 1880 | -0.3 |
| 1900 | -0.1 |
| 1920 | -0.8 |
| 1940 | -0.6 |
| 1960 | -0.5 |
| 1980 | -0.4 |
| 1990 | -0.1 |
| 2000 | 0.2 |
| 2004 | 0.6 |

Below we describe some of the changes occurring
in ice melting, sea level rising, and atmospheric temperature rising.
The ice melting in the Arctic Ocean has been quantified, calculated, and depicted characteristically between the years of 1979 and 2003 (a 25 years time period), from images based on satellite data. There is a sharp reduction of sea ice, especially at the ends of the arctic, by the year 2003, which is shown in these satellite images. Vast areas of open seas have appeared near Alaska, Canada, and Russia replacing the perennial ice sheets covering the sea in the years before, especially in summer. Some climate models predict that the Arctic sea ice probably will diminish dramatically by the end of the 21$^{st}$ century. It is expected a reduction of about 38% of the sea ice volume by the year 2100 and beyond.
Also, one can see that the projected sea levels rise substantially from the increase in the anthropogenic $CO_2$ emissions and the related weather events become extreme. As example, sea levels are expected to rise at about 4-5 inches at the 478 ppm level of atmospheric $CO_2$ concentrations. Furthermore, the sea rise is expected to be about 3 feet, at 971 ppm projected level of atmospheric $CO_2$ concentrations, [4,10].
In addition, the average Northern Hemisphere surface temperature is expected to rise throughout the years as the measured $CO_2$ concentration in the atmosphere also rises respectively in the same years. The temperature data comes from ice-core, tree-rings, and lake sediment samples using related instrument readings. $CO_2$ concentrations have risen from about 285ppm level in 1860s at surface temperatures of about 57.6°F, to the current 380ppm $CO_2$ level in 2004 year at an increased surface temperature of about 60°F, [1,3,17].

Catastrophic events of a continuous global warming effect include: massive melting of polar ice sheets and major rise of the sea level, sudden climate changes caused mainly by the dramatic slowing of the existing oceanic current systems, disappearance of species habitats with subsequent species loss, permanent loss and disappearance of glacier-fed ancient waters especially from glaciers of India, China, South America, and African countries. These countries can play a much bigger role in curbing and stopping pollution, which is coming from and relating to carbon dioxide and other greenhouse gases. It may take several years and even decades to stabilize the current greenhouse gas emissions and the related atmospheric, sea, and ocean warming, even by applying today zero or near zero-emission power generation and automobile technology such as fuel cells and advanced fuel cell stacks [12,13,16,17].

In addition to $CO_2$ sequestration and storage, energy efficiency improvements, and switching to less-intensive fuels, hydrogen fuels, fuel cells, high efficiency vehicles and renewable energy need to be searched and implemented [1,3,5,12-17].

IPCC was created in 1988 by the UN Environment programmer and the World Meteorological Society with expert scientists around the world to advance the knowledge of the climate change and its unparalleled complexity and effects. IPCC issues a number of pertinent environmental reports.

These related reports are taking into account current intense energy usage, high population increase, and economic activity data which are reported by governments and published in peer reviewed literature, and are largely based on consensus.

IPCC has concluded by widely accepted statements that temperatures are rising, snow cover and precipitation is diminishing, glaciers are retreating and contracting, and droughts are more frequent and severe and last longer. Previously cultivated areas are converting to deserts due to longer droughts and diminishing or loss of water sources. The Artic and arctic sea is warming much faster than anticipated according to several Impact Assessments [3,4,7,9,10,11,14].

The $CO_2$ concentration in the atmosphere has increased about 30% by 2008 since the industrial revolution. According to the IPCC model runs, the global average surface temperature will increase between 1.4 to 5.8 $^oF$ from 1990 to the end of the 21st century. Winter temperatures will rise especially in the northern areas. Globally, the average water vapor concentration, evaporation, and precipitation will increase. This effect will result in an increase in sea levels from about 0.09 m to 0.88 meters within this time period [2,3,4,8-11,14,17].

As the polar ice cap continues to melt at faster rates than expected and as heat expands water, the sea levels will rise. Incoming heat waves and droughts in many parts of the world, can increase the number of these killed by heat. Rates of infectious and heat-related respiratory diseases may increase. Economies will be affected, and several people may be dislocated.

All forms of life and mostly endangered species, because of their dependence on temperature, will be affected with severe ecological consequences.

A broad range of actions should be considered and taken within short time to stabilize climate including not only $CO_2$ concentrations but also other climate forcing, affecting agents such as methane, trace gases, black carbon and aerosols.

Regarding the atmosphere's composition, changes have been observed over 150 years. The greenhouse gases absorb energy, especially from the sun, that is balanced by evaporation which can lead to an increase in rainfall. The rainfall can be the source of fresh water making the atmosphere colder. Measuring the ocean salinity, has proven that in the past decades and years the ocean has gained extra fresh water. Incoming atmospheric conditions expect to affect (e.g., warm or cool) the planet including solar irradiance, tropospheric and stratospheric aerosols and other. Scientists are trying to insert all these information in models (i.e., climate, atmospheric, ocean models) to predict the results in incoming climate changes and dominant climates for the next several years. The dramatic tsunami which happened on Dec. 26, 2004 in Indonesia and parts of Africa and India by the dramatic increase of the water height in the Indian ocean, shows the power and intensity of oceanic and climate changes, and their catastrophic effects on human population and its establishments.

That was followed by the deadly tropical cyclone Nargis which took place in Myanmar on May 4, 2008. It devastated an area of about 5,000 $km^2$ and flooded the entire delta close to the city of Yangon. About 30,000 people lost their lives and almost double were missing by the fierce cyclone which brought sudden winds of up to 120mph.

This 2008 fierce cyclone can be compared with the 1991 devastating cyclone in the neighboring country of Bangladesh which killed about 143,000 people.

"Global warming is a modern problem complicated, involving the entire world, tangled up with difficult issues such as economic development, poverty and population growth. Dealing with it may not be easy but ignoring it will be much worse".

IPCC reports an about 1.4% growth in $CO_2$ emissions each year. The largest source of this contribution is from the transportation sector/factor exceeding the one from industry. The highest $CO_2$ contributions are coming from automobiles, light and heavy trucks. The possibilities of avoiding climate changes by eliminating the transportation and stationary $CO_2$ emissions are here technologically and from an application point of view.

Technology and technical implementation can fix the problem by itself: it has to establish the policy framework, the technical and safety conditions in which the proposed alleviation technologies can be developed and applied. According to the quote of related experts, "we have to redefine technology-related priorities within a global framework".

## 2. Studied Area

Below we provide useful data and some technical projections on the sources of $CO_2$ emissions, including treatment methods and related fuel cell plants under operation.

Economically speaking, stabilizing the $CO_2$ concentrations to a reasonable value of less than about 400 ppm by 2050, can reduce the global GDP by only 4%. Millions of barrels of oil can be saved by 2030, the cost of oil can be dropped to about $40 per barrel, with estimated savings of about $100 billions per year, [5,12,17]. These estimations come in comparison with the 2007 steep oil prices of nearly $90-$100/barrel, and the even steeper oil prices of nearly $100-$145/barrel in 2008.

There is a need for continuous global vision and commitment to reduce emissions in the above referring stationary and transportation sectors and sources. The scientific and technical community worldwide has to present it and achieve it.

The comparative Table 2 below, shows the amount of exhaust emissions per power system for several types of power stations.

The impact of fuel cells on the environment can be highly beneficial, with minimal emissions from the exhaust gases, because fuel cells can generate clean power. The Table 2 below, includes also the exhaust emissions from the 1 MW prototype natural gas burning fuel cell plant, developed and tested by the United Technologies Corporation. It is clear that its emission level is much lower than that permitted and seeked by the USEPA.

Moreover, according to a study funded and applied by the EPA, fuel cells not only are more efficient and environmentally benign than conventional power units, but also the same advantages are apparent from the resource extraction stage to the final end use plant of the generated electricity. The recent fuel cell NOx emissions are very low and in the second generation fuel cells with improved cathode chemistry these emissions can be negligible. Improved methods for the separation and detection of emitted pollutants are required to ensure a safe and continuous operation of fuel cells and related low emissions power equipment, [9,11,12,16,17].

The above observations give a tentative quantitative measure of the current fuel cell markets and their upcoming technical potential in several sectors, especially in the stationary and transportation power generation.

The Intergovernmental Panel on climate change (IPCC) expects that global temperatures will rise by about 2 to 6 degrees Fahrenheit around the globe during the 21st century. A significant economical fallout is possible to be observed and take place from such an important temperature increase.

According to the researchers who studied and estimated these changes, such an increase in temperature in North America, can result to about 1.1% damages of the United State's gross domestic product, that is roughly about $90 billion dollars. Similar projections are made for the remaining continents, including fragile entities such as in Asia, Africa, and Oceania.

Therefore, there is an urgent need to have a global, local, and flexible market based effort to decrease the impact of high emissions energy generation on the global climate, especially at key sensitive factors and areas.
Economic studies have shown that there are many potential policies to reduce greenhouse gas emissions for which the total benefits outweigh the total costs.
Fuel cells, renewable energy sources, and related environmental units and systems are potential and long term viable solution to the above expected drastic environmental changes.
Technological leadership and clean technical solutions are critical points of the market based solutions, to mitigate global climate changes. These facts and necessities require a high degree of investment in research and development, [1,2,5,7,11,14].
Moreover, this modern technology investment has to be combined with cooperative connection with industry, academia, business leadership, political law and other sectors to find suitable and effective, technical and economical solutions.
The potential for fuel cell technology applications is huge. The domestic and mostly the international market for future power generation are tremendous. For example, China alone has shown that is going to add about 20GW of electric generating capacity per year for the next 10 to 20 or more years, which represents a huge market size from $15 to $25 billion dollars annually. Similarly, with the power installations in India, Brazil, and Africa.
Significant progress and discoveries have been done in fuel cell technology during the last years, and complete commercialization is underway. Continued technological progress and related fuel cell developments and installations towards ushering in a new era of electric power generation will be established. Future power generation will be focused into clean, efficient, and low cost sources, and capable to produce continuous electricity as well as other high value byproducts such as chemicals (e.g., hydrogen, hydrocarbons, alcohols, polymers, etc) and heat, [12,13,15-17].
The Kyoto protocol of 1997, is the culmination of a series of meetings and conference activities that began in 1992 in Rio De Janeiro, Brazil, directly related with the elimination of the potential greenhouse threat.
One important activity was the creation of the Intergovernmental Panel on Climate Change. A 1995 IPCC report that consolidated the efforts of more than 2,000 prominent climate scientists from all over the world where more than 50 countries were represented, synthesized data and draw valuable conclusions.
Highlights of the most important findings can be summarized as follows:
1) Carbon dioxide concentrations, currently at about 360 ppm, could surpass 700 ppm by the year 2100 if the world persists in “business as usual” in greenhouse gas emissions from power generation and fossil fuel usage; this effect could result in a temperature increase of

2 to 6.5 $^{o}$F during this (21$^{st}$) and the next century (22$^{nd}$).
2) The global water cycle would be affected by higher temperatures, leading to droughts from faster evaporation, and an increase in precipitation due to accelerated global cycling of water.
3) Sea levels could rise by as much as 4 to 37 inches.
4) The above changes would have a significant impact on weather patterns, agriculture, forests, jungles, arctic glaciers, and other earth, water, and sea ecosystems, also on human health and overall well being.
The 1995 IPCC assessment was instrumental in prompting the need to construct, debate, and ratify a "world treaty on global climate change". At Kyoto, leaders in government, science, and industry aggressively pursued this goal and for first time in history formed a consensus to reduce greenhouse gas emissions. The Kyoto treaty calls for a reduction of the overall greenhouse gas emissions by industrialized countries in the period of 2008-2012 years, to amounts at least 5% below the 1990 levels.
More than 160 countries have signed and ratified the treaty to curb the $CO_2$ emissions, which are mostly generated by about thirty five or more industrialized countries. Industrialized countries must support and expand new energy efficient and renewable technologies and power plants in developing regions. This includes clean fuel cells applications and fuel cell power plants.
About 700 new power plant projects from the Kyoto treaty are in the waiting list today for developing countries. About 42% of those are in South and Central America. Thus, the main accomplishment of the Kyoto conference/treaty is the specification of emissions targets especially for developing nations during the next decades. These emissions targets are different for each country and set binding limits of compliance for each participating government.
The recent Bali conference for Climate Change in Indonesia on December of 2007 under the auspices of the United Nations Environmental Committee had delegates from several countries, who voted to renew the commitments of the Kyoto protocol for the continuous global reduction of greenhouse gas emissions from stationary and transportation emission sources. New future international conferences (i.e, Copenhagen, Denmark 2009) were scheduled and completed in order to renew, detail, and update the waste greenhouse-gases reduction treaties and to uphold the Kyoto's conference environmental vision and commitments.
It is important for the climate change effects not only to be observed but also to be specifically analyzed, verified, and justified with statistical techniques. Statistical methods are presented here based on specific tests that can verify the measured data. Computer simulations can give results that are helpful for further estimations and predictions, in order to figure out critical points and conditions that are derived from environmental data.

## 3. Results and Discussion

Almost the 22% of all $CO_2$ emissions released annually comes from cars on a global basis. There are about 550 million cars in the roads every day.

Concentrations of $CO_2$ are about 35% higher today than before the industrial revolution. USA alone releases almost the 25% of the global $CO_2$ emissions from the burning of fossil fuels each year.

The world's $CO_2$ emissions will increase by almost 1.5-2% annually between 2001 and 2025. Deaths from global warming will double in the next 25 years to 300,000 people dying per year from various effects. More than one million species will be in danger to be driven to extinction by 2050. The number of category four and five hurricanes has almost doubled in the last 30 years. There was a net temperature increase of about 1.2-1.4 ◦F in the last 40 years due to the increase in greenhouse gases concentration in the atmosphere. There is the expectation of an about 2.0-6.5◦F increase in temperature by the end of this century. Some of these phenomena described above, can be studied and analyzed further using the values of the table that follows [4,10,17].

The table shows the incremental rise of the sea above the current sea level within the recent years.

**Table 3. Predicted sea level rise at two different $CO_2$ concentrations at recent years.**

| Years | Rise above Sea Level/(in) Best Case ($CO_2$ at 478ppm in 2100), (global average) |
|---|---|
| 2000 | 0.0 |
| 2002 | 0.1 |
| 2004 | 0.4 |
| 2006 | 0.6 |
| 2008 | 1.0 |

| Years | Rise above Sea Level/(in) Worst Case ($CO_2$ at 971ppm in 2100), (global average) |
|---|---|
| 2000 | 0.0 |
| 2002 | 1.0 |
| 2004 | 1.5 |
| 2006 | 2.2 |
| 2008 | 3.0 |

Observed data (from the above table) regarding the increase in the sea level due to the increase in the $CO_2$ concentration in the atmosphere for both best case and worst case scenarios are analyzed. A substantial increase in the sea level during the last six decades of the model prediction, for the worst case scenario can be observed (e.g., 2040-2100 years, Table 4 below).

The values become critical, with negative/bad consequences globally as the years pass. For example, in the country of Bangladesh at just over 3 feet of rise above the sea level, about 70 million people could be displaced. Almost 75% percent of the coastal area of Louisiana wetlands could be flooded at a sea rise of 1.5 feet. In another scenario, many low-lying South Sea Islands (Figure 6 below) are at further risk of flooding at only about 4 inches. Analytical statistical study, based on the above data, has been performed using specific statistical and optimization packages/algorithms named MINTAB. Running a regression analysis program one can obtain all the necessary statistical and other parameters for this simulation [6,17]. First, the corresponding regression equation for both cases (Figure 1) is obtained as follows:

from the sample data using the corresponding standard deviations.

The test is called "oneway analysis of variance" coming from the analysis of the variance hypothesis test. The F calculated here is 80.14 with the degrees of freedom (1,3). Reading the tables of the F distribution [6], by reading down column 1 for row 3, we take F to be 10.13.

If the value $F_{calc}$ is greater than $F_{table}$ then we conclude that on the basis of the sample evidence there is a link as it was given above by the regression equation which is valid.

Here, it is found that $F_{calc}$ (80.14) > $F_{table}$ (10.13).

The statistical analysis also gives all the descriptive statistics

**Rise above the Sea level (best case) = -250 + 0.125 * Years**

The square of the coefficient of determination is 94.4% which satisfies the specifications for the hypotheses criteria so that a relationship exists between the rise of the sea level with years (Figure 1). Moreover, the defining decision rule can be concluded by the F ratio calculated

Since the median value is very close to the mean value, the distribution is symmetrical. These statistical measures are important to verify the analyzed data and their characteristics.

Moreover, for the worst case scenario the regression equation according to the data of Figure 1, is:

**Rise above the Sea level (worst case) = -719 + 0.360 * Years**

Mean St. Dev Min Q1 Median Q3 Max Skewness

The square of the coefficient of determination here is 91.1% which satisfies the specifications for the hypotheses criteria so that a relationship exists between the rise of the sea level with years. Moreover, the defining decision rule can be concluded by the F ratio calculated from the sample data using the corresponding standard deviations.

The same test is performed. The $F_{calc}$ here is 326.91 with the degrees of freedom (1,3). Doing the same comparison as before for the $F_{calc}$ and the $F_{table}$, we conclude that on the basis of the sample evidence there is a relationship as it was given above by the regression equation which is valid. The statistical analysis also gives all the descriptive statistics:

. 0.42 0.40 0.002 0.051 0.40 0.8 1.0 0.61

The same test is performed. The $F_{calc}$ here is 326.91 with the degrees of freedom (1,3). Reading the tables of the F distribution [6], and reading down column 1 for row 3 we take the $F_{table}$ to be 10.13.

Here, $F_{calc}$ (326.91) > $F_{table}$ (10.13).

| Mean | St. Dev | Min | Q1 | Median | Q3 | Max | Skewness |
|---|---|---|---|---|---|---|---|
| 1.54 | 1.143 | 0.002 | 0.501 | 1.5 | 2.6 | 3.0 | -0.11 |

Since the median value is very close to the mean value, the distribution is again symmetrical.

The corresponding statistical figures of the regression equations for both cases, boxplots (where we can see the min, max, Q1, Q2, Q3) and histograms are shown in Figures 2, 5, and 6.

**Projections for the next decades**

The meaning of the regression equations described above is of high importance, because they can assist us in predicting the evaluation of the corresponding phenomena which will happen at the later years and estimate their critical conditions, performance, and results.

As an example, using the regression equations listed above, one can predict the following results for the coming years 2020, 2040, and 2100:

**Table 4. Projections for the 2020, 2040, 2100 years.**

| Years/Result | 2020 | 2040 | 2100 |
|---|---|---|---|
| Rise above sea level (bc/in) | 2.5 | 5 | 12.5 |
| Rise above sea level (wc/in) | 8.2 | 15.4 | 37.0 |

Furthermore, Fig.1 below verifies the above results. Fig.1, plots the projected sea level rise based on different observations and estimations [3] and agrees well with the results listed in Table 4.

Also, Fig.7 below shows the dramatic effect of sea level rise on the earth's population (on a global basis) for many low lying earth areas [3]. According to the Figure, there are already areas in Oceania which are affected by the sea level rise from the undergoing greenhouse and climate changes.

Figure 4 below, depicts the effect of modern reaction and fuel conversion technologies for the production of renewable hydrogen for end use in fuel cell systems. Hydrogen can be produced in an economical way from these technologies including solar membrane reactor technology for fuel cell applications [17].

Fig.4 depicts the flow rate of hydrogen as a function of two other reaction parameters in a membrane

based reactor. Here, hydrogen is produced from the propane dehydrogenation reaction and can feed a fuel cell system for electricity generation.
In a coming hydrogen economy it is important to define economical and renewable feedstocks and to develop technologies with high efficiency, capacity, yield, and reliability. Work in this area is underway [9,17]

## 4. Conclusions

One can imagine the consequences of the effects that the above numbers in rising $CO_2$ earth concentration, temperature, and sea levels can have to the environment, planet's life, infrastructure, and current civilization. The statistical studies described here can contribute in many aspects to the observation, analysis, and scientific implementation of such essential and vital factors and phenomena as discussed above.
It is necessary therefore, to apply now new energy efficient and renewable energy technologies as fuel cells, fuel cell stacks, and hydrogen power systems. These efficient and environmentally benign technologies must be applied in the transportation and stationary power generation sectors. They also guarantee the reduction of harmful emissions at very low levels.
Statistical analysis and related estimations and models are necessary tools in gaining knowledge of the consequences and effects of the incoming climate changes. It is necessary that these effects are both qualified and quantified at their best.
Some researchers can estimate the climate changes occurring by using different models and parameters and other types of simulations and predictions which may give more aggressive changes and results for the future years. But in most cases, the modeling results are within the same wider ranges.

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**Table 2; Comparison of exhaust emissions for various Power plant systems; (kg /1000kWh)**

| Contaminant type: | SOx | NOx | Particulates |
|---|---|---|---|

**Type of power station:**

| | | | |
|---|---|---|---|
| Gas-fired | ---- | 0.89 | 0.45 |
| Oil-fired | 3.35 | 1.25 | 0.42 |
| Coal-fired | 4.95 | 2.89 | 0.41 |
| Fuel Cell | $4.6x10^{-5}$ | 0.031 | $4.6x10^{-5}$ |
| EPA desired limits | 1.24 | 0.464 | 0.155 |

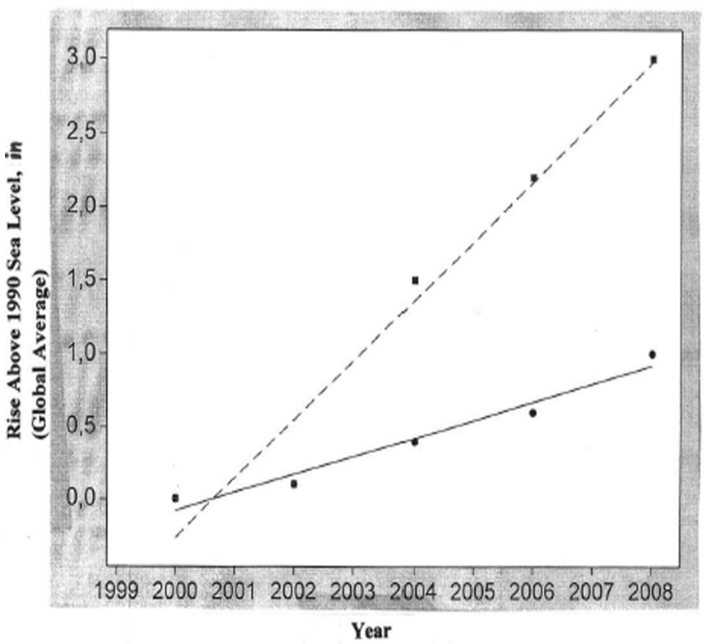



Fig. 1.

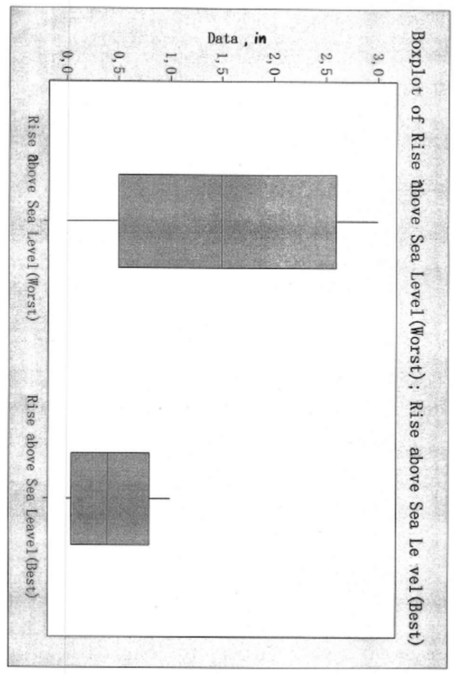
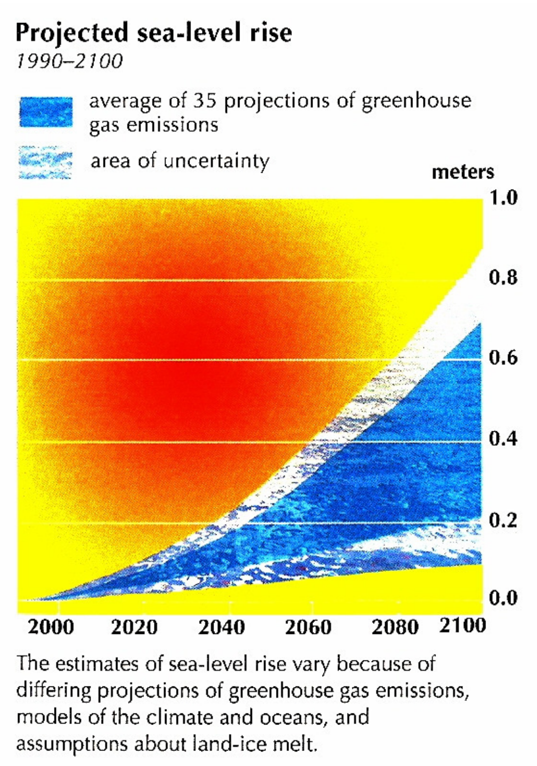
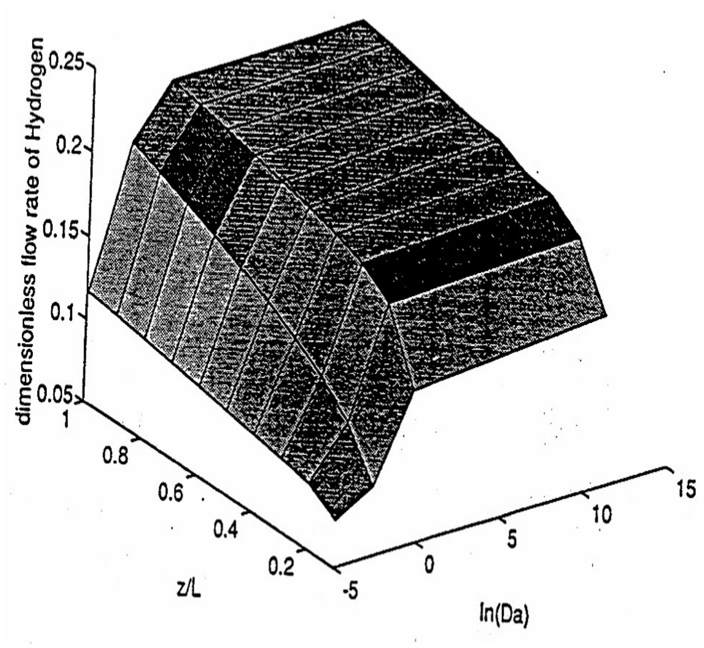


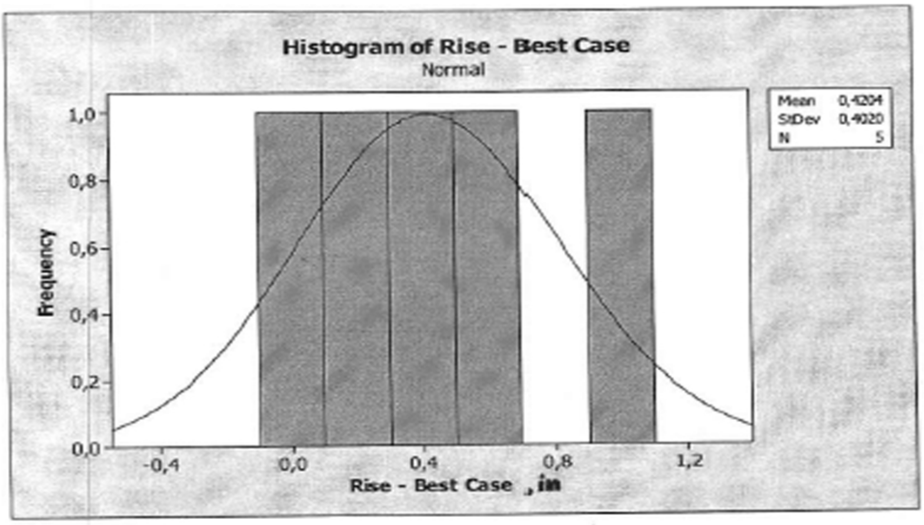

Fig. 2.

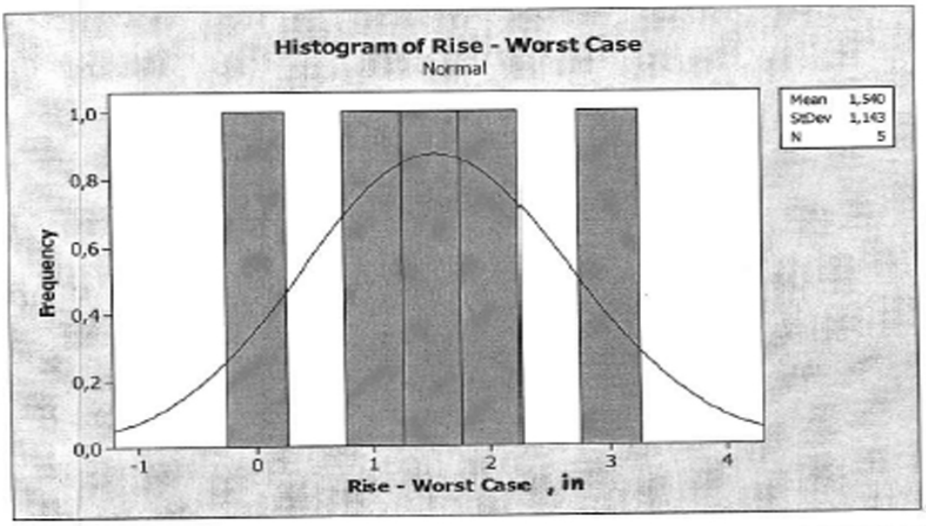



**<u>Fig. 3.</u>** Fig.4

**Fig. 5 and Fig.6.**


Histogram of Rise - Best Case
Normal
Mean 0,4204
StDev 0,4020
N 5
Frequency
Rise - Best Case , in


Histogram of Rise - Worst Case
Normal
Mean 1,540
StDev 1,143
N 5
Frequency
Rise - Worst Case , in

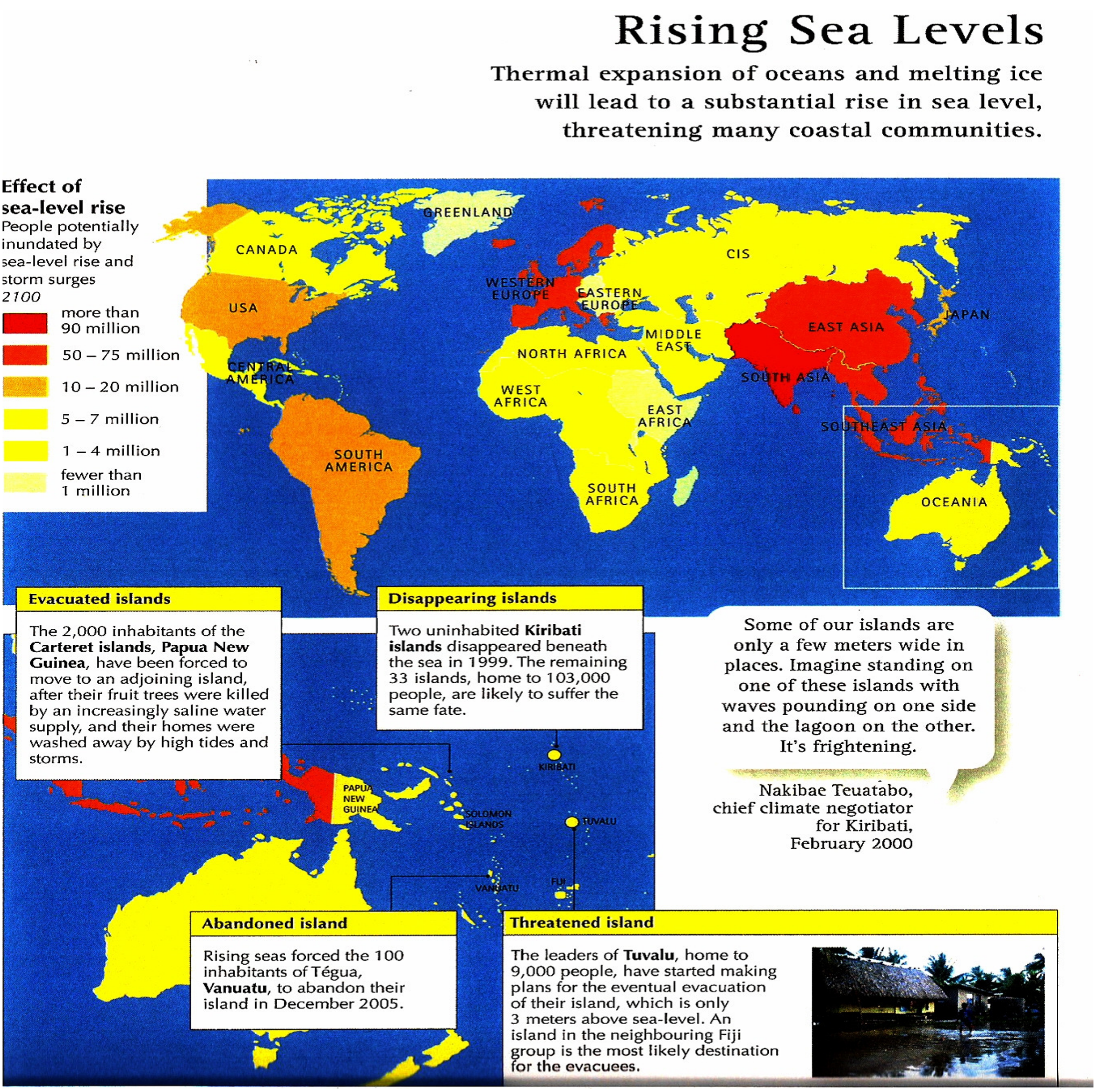

Rising Sea Levels
Thermal expansion of oceans and melting ice will lead to a substantial rise in sea level, threatening many coastal communities.
Effect of sea-level rise
People potentially inundated by sea-level rise and storm surges 2100
more than 90 million
50 – 75 million
10 – 20 million
5 – 7 million
1 – 4 million
fewer than 1 million
GREENLAND
CANADA
USA
CENTRAL AMERICA
SOUTH AMERICA
WESTERN EUROPE
EASTERN EUROPE
CIS
MIDDLE EAST
NORTH AFRICA
WEST AFRICA
EAST AFRICA
SOUTH AFRICA
EAST ASIA
JAPAN
SOUTH ASIA
SOUTHEAST ASIA
OCEANIA
Evacuated islands
The 2,000 inhabitants of the Carteret islands, Papua New Guinea, have been forced to move to an adjoining island, after their fruit trees were killed by an increasingly saline water supply, and their homes were washed away by high tides and storms.
Disappearing islands
Two uninhabited Kiribati islands disappeared beneath the sea in 1999. The remaining 33 islands, home to 103,000 people, are likely to suffer the same fate.
Some of our islands are only a few meters wide in places. Imagine standing on one of these islands with waves pounding on one side and the lagoon on the other. It's frightening.
Nakibae Teuatabo, chief climate negotiator for Kiribati, February 2000
KIRIBATI
PAPUA NEW GUINEA
SOLOMON ISLANDS
TUVALU
VANUATU
FIJI
Abandoned island
Rising seas forced the 100 inhabitants of Tégua, Vanuatu, to abandon their island in December 2005.
Threatened island
The leaders of Tuvalu, home to 9,000 people, have started making plans for the eventual evacuation of their island, which is only 3 meters above sea-level. An island in the neighbouring Fiji group is the most likely destination for the evacuees.

Fig. 7.

# Impact of climate, geography and economic structure of each country on $CO_2$ emissions

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**Abstract:** Several authors correlate the emissions of $CO_2$, which is the main greenhouse effect gas, with the per capita income of each country and report that there is an inverted U-shape curve in this correlation (Environmental Kuznet Curve). Several models can be found in the literature, and most of them do not give satisfactory results. This work reviews initially the most important of those models and presents their major advantages and disadvantages. In a second place a new methodology is proposed. This methodology is not based only on the per capita income, but also on several other parameters which can be divided in three groups. First group is the climatic conditions of each country (such as mean annual temperature), second is the anthropo-geographical parameters (such as population, number of megalopolis, population distribution, surface of the country, transport infrastructure, etc.) and third the economic structure of each country (such as percentage of primary, secondary and tertiary sector, imports/exports, unemployment percentage, etc.). This methodology can also be adapted in the case of energy consumption and the emissions of other gases, such as sulfur and nitrogen oxides.

**Keywords**: $CO_2$ emissions, Environmental Kuznet Curve, climate changes

## 1. Introduction

Climate changes have been in the centre of environmental and economic concerns during the last years, since they constitute the basis of extended research about the causes, the consequences and the possible policies that could improve this trend over time. Facing greenhouse effect gases (GHG) emissions is a complicated and long-termed situation. The main causes that led to this situation seem to come up from the growth of today so-called developed economies over the previous decades: their development based on industrialization combined with relatively cheap energy mostly from the use of fossil fuels. But the use of fossil fuels led to the increase and over-accumulation of GHG emissions in the atmosphere above the rate that nature itself could sustain. Possible effects on the environmental systems are evident, and systematic solution need to be undertaken, since $CO_2$ which constitutes the major element of GHG is supposed to remain in the atmosphere for about 5-200 years. On the other hand, $CO_2$ emissions are directly related to energy use, which is an essential factor in the world economy. Therefore, the specific relationship between $CO_2$ emissions and economic growth has important implications for environmental and economic policies (Azomahou et al 2006).

The particular relationship between the growth of an economy and the environmental degradation can be found in several works dealing with the so called Environmental Kuznets Curve (EKC). In general, the EKC implies that an inverted U relationship between economic development and environment quality exists. Its origin is the inverted U relationship between inequality and income presented by Kuznets (1955). This relationship was examined by many authors on environmental subjects suggesting that economic activity is based on primary resources at low levels of development. As industrialization takes off, resources depletion and waste generation accelerate. Finally at higher levels of development, industry is more information based and services and technology are more efficient. The above statements in combination with the increased demand for environmental quality result in a decline of environmental degradation (Panayotou 2003). Many of those studies try to examine empirically this relationship and their findings show the detection of such an inverted U relationship between income and emission of some air gases ($SO_2$, CO, NOx) and water pollutants (nitrates, heavy metals, fecal coliform) (Prieur 2009). Some researches have attempted to explain this inverted U relationship as the result of the impact of trade openness and the international mobility of production factors (Aslanidis

2009). The main conclusion of those studies is that heavy polluters move from high-income countries with strict environmental regulations to low-income countries with weaker environmental regulations, so it seems that we face an export of pollution from richer to poorer countries (pollution haven hypothesis). In terms of international trade, changes in consumption behavior can be included to interpret changes in emissions (Rothman 1998). In general, three forces seem to affect the relationship between economy growth and environment: changes in the structure of production through technological improvements, changes through trade with import of pollution intensive products and changes of consumer behavior on environment as economic growth accelerates.

In relative literature, many authors attempted to include the influence of other possible variables that may affect the income – environment case. Income inequality can reduce an economy's willingness to invest on environmental improvement (Aslanidis 2009). Even the corruption of the political-economic system can reduce the effectiveness of environmental policies since citizens do not trust enough their political authority (Aslanidis 2009). Income distribution, education and information access probably affects society's choice for environmental quality (Bimonte 2002). For Dinda (2005), a shift from insufficient to sufficient investment to upgrade the environment is the basis for the decrease of pollution level, and forms the inverted U-shaped relationship between pollution and economic growth.

Several authors have already surveyed critiques on most of the studies on EKC relationship. Stern D et al (1996) sets out and reviews primary studies. A historical throwback over the EKC research and the basic assumption introduced by corresponding authors was presented by Dinda (2004). Next year, Nahman and Antrobus (2005) review some studies and the critiques on those studies. Recently, Aslanidis (2009) in a critical survey reviews the econometric techniques that have been adopted in many studies, listing their major advantages and disadvantages.

Although in most of the relative literature, an evidence of an EKC relationship has been found for many pollutants, little evidence shows that an EKC hypothesis holds in the case of $CO_2$, and if it holds, it does so for very high levels of income (Panayotou 2003). If such a case stands for $CO_2$, then it would be reasonable to assume that economic development would ultimately lead to a decrease of global emissions. But as societies become richer, they may want to improve their own environment but they can do little about climate change by reducing their own $CO_2$ emissions alone; the global nature of the externality of $CO_2$ emissions implies that agents in any particular high-income country cannot significantly affect global emissions and hence their own climate (Stern Review, p.191). Maybe the EKC relationship is observed for short – lived pollutants (like sulfur oxides or oxides of nitrogen) having a more local and less global impact on the environment, while accumulated pollutants like $CO_2$, seem to be positively related to income and constantly increase with it. As an additional point of concern, nature cannot absorb pollution levels over the natural rate and thus any attempts to invert the over-accumulation of $CO_2$ in the past would be unsuccessful (Prieur 2009).

The relationship between economic growth as is represented by income per capita, and the environmental degradation as represented by emissions per capita, is an important item for further research. In general, an EKC relationship is not robust enough and several questions arise about the main determinants of this relationship. For this reason we need to define the special characteristics of an economy that diversifies its growth process from the other economies and affect its own environment and the global environment in general. This definition is a major basis of the current study which is prefacing with the present publication. The additional parameters that shape the final production (income) and provide developmental characteristics can be grouped in three categories, the geographical and anthropo-geographical conditions, the climate conditions, and finally some additional macroeconomic parameters. The specification of those categories is developed in the next section.

## 2. Proposed Methodology, Inspection of Parameters

*1) Geographical – Anthropogeographical Parameters*

According to World Bank, the next decades world population is expected to increase for about 2-3 billion people, with the biggest increase rate to show in developing countries (Stern Review, p.96). Population plays an important role in $CO_2$ emissions (Gaffin and O'Neill, 1997). In many estimations based on Malthus thought about population, an a priori assumption that population growth is connected strait with environmental degradation and $CO_2$ emissions, implies that policies to govern population growth need to be adopted in order to protect environment (Hunter 2000, p.11). For Cropper and Griffiths (1994) there is no doubt that population growth contributes to environmental degradation, but its effects can be modified by economic growth and modern technology. Hamilton and Turtor (2002) concluded that income per capita and population growth are the main two factors that increased carbon emissions in OECD countries over the period 1982-1997.

A more interesting parameter seems to be the rate of urbanization in an economy which is connected with the existence of big urban areas. Historically, urbanization is associated with the strengthening of economic growth process. The rate of urbanization in developed and developing countries grows fast (Hunter 2000, summary xii). Cities are often described as a "growth machine" that requires energy consumption to maintain the daily operations of the economy, to support the movement of people, and to meet human needs. Thus, urbanization is connected positively with increased $CO_2$ emissions through energy consumption.

As regards this case, it is important for the current study to associate the existence of little but large megalopolis against the existence of many but relatively small megalopolis in a country. Our thinking is that big cities (megalopolis) that concentrate a comparably large percentage of total population can be more efficient in energy consumption terms (for example, with the existence of more efficient transport infrastructures that serve at the same time many people, or with the existence of apartment blocks combined with central heating systems).

Jorgenson et al (2010) indicates that the effect of urban population growth on energy consumption increase is supposed to be positive, but the increase of energy consumption is negatively associated with the growth of the percentage of the total population living in urban slum conditions. For Martinez-Zarsoso (2008), the urbanization case is different. The effect of urbanization on $CO_2$ emissions depends on the income of a country, implying that when urbanization reaches a certain level, the effect on emissions turn out to be negative, contributing to reduced environmental damage.

Migration of people is also an important parameter and is placed among the international flows of labour. Migration also occurs due to wars and to other reasons. People migrate not only inside an economy (by moving in big urban areas as discussed previously) but to other economies (countries) too and they concentrate to big cities. Labour migrates legally or illegally from low to high income countries. Migration can be limited by immigration laws, transportation cost, lack of information about job opportunities and language differences, but in most of Europe and United States the percentage of immigrants in population and workforce have risen during last years (Dunn and Mutti, 2004, p.205).

The importance of geography as an economic growth parameter is not new in economic literature, but the recognition of geography's direct impact through climate and natural resources in economic development is relatively recent. Bloom and Sachs (1998) proposed that tropical geography (natural environment) and demography played a crucial role for the non development of the African economy. The capability of an economy to have access to sea plays also a major role in economic development, as countries placed away from sea don't follow the usual economic development due to high transport cost (Gallup et al, 1999). More an economy is away from sea-access, more unstable appears in terms of trade and production, because of limited alternative ways for exportation (Malik and Temple, 2009).

The surface of a country (mountainous or flat), the distance from markets and in accordance, the existence of sufficient transport infrastructure, is an important geographical factor. According to IEA 2009, transport is responsible for the ¼ of global energy-related $CO_2$ emissions. Car ownership is expected to triple and reach 2 billion by 2050 (IEA 2009). Transport using trucks is also expected to double, and air travel could increase four-times (IEA 2009) while at the moment cars and trucks are responsible for the 70% of GHG emissions from the transport sector (Dow and Downing 2007, p.46). In developing countries of Latin America, the growth of transport during the last years was associated with economic growth but also with the increase of $CO_2$ emissions (Timilsina and Shrestha, 2008).

*2) Climate Conditions*

One consequence of climate change is the increase of globe's average temperature and one challenge of the current scientific research is to estimate the future average temperature (IPCC AR4). Most of the current scenarios estimate that the increase of average global temperature will overcome $1^oC$ in 2050 and probably reach $6^oC$ till the end of the century (Dow and Downing, p.36). Several scenarios show the possible effects of the average temperature increase on economies and environment (Stern Review p.147). One of the main ideas of current study is to take in account the climate conditions of each country using meteorological parameters as the average annual temperature. Literature indicates that warmer countries are in general poorer (Horowitz, 2009). Climate in combination with geography, implies that countries with "favorable" geographical and climate structure (cool, coastal, frequent rainfalls), appear high incomes in contrast to hot (landlocked, with low rainfall) countries although such a simple geographic determinism is rejected as an explanation of large differences in income levels among countries (Bloom et al, 2003). But locally, the level and variations of average annual temperature of a country is an important parameter for the $CO_2$ emissions of that country. For example, short but extreme temperature increases have as a consequence higher energy consumption due to the intensive use of air-conditioning systems. Reversely, extreme decreases of temperature lead to increased use of energy consumption for heating. A previous study (Considine 2000) reports that warmer climate conditions in the US since 1982 slightly reduced carbon dioxide emissions in the US, so the impact of short-term climate fluctuations on $CO_2$ emissions can be significant.

Additionally, the extend of economic development combined with temperature fluctuations outlines various effects: as developing countries are located in tropical areas, they are more vulnerable to extreme climate changes (floods, droughts, high temperatures) because their economy is mostly based on agriculture and ecosystems (Stern Review, p.94). As Nordhaus (2006) notes, tropical geography has a substantial negative impact on output density and output per capita compared to temperate regions. Countries in the low latitudes start their growth with very high temperatures and further warming pushes these countries ever further away from optimal temperatures for climate sensitive economic sectors (Stern Review, p.95). Poor countries are more vulnerable for two reasons: not only they are more exposed to climate changes, but also their ability to face extreme climate chances (adaptive capacity) is limited by their low-income economies (Tol et al, 2004).

*3) Economic Parameters – Economic Structure*

One of the most used indicators to describe the economic development of a country is income per capita which is the gross domestic product (GDP) divided with the population of the economy. However, this indicator does not contain quality characteristics, so additional parameters must be considered in order to obtain a better image of economic activity and development.

In product terms, the production process is allocated to the primary, secondary and tertiary sector. Over time, the participation of each sector in total production of each economy is not constant. Historically, an economy's development process begins from agriculture, turns to industrialization and as economy growths, the service sector is boosted. The services sector gains diachronically a continuously bigger share of total production. The question that arises is what is happening with the energy consumption that is connected with the productive sectors of the economy. For example, according to EIA data about the $CO_2$ emissions from the final energy consumption by sector in USA, the $CO_2$ emissions from the industry sector decreases over time, while commercial and transportation emissions increases. Transportation and commercial are parts of the tertiary sector[17]. Transportation, which is the most important part of services, is mainly based on fossil fuels (oil) and naturally is combined with high degree of $CO_2$ emissions. According to Nansai et al (2009), in Japan, the increased energy use and consequently the increased $CO_2$ emissions in the tertiary sector occurred because of the production of materials for the support and consumption of services.

Another important parameter of economic activity is the international trade and the relationship between imports and exports of goods (products and services). The importance of trade is ultimate in economic theory, as trade improves technology through the distribution of information, and helps economies to develop their comparative advantage. For Grossman and Helpman (1990) economies that adopted an outward-oriented development trade strategy, have grown faster and achieved a higher level of economic well-being than those that have chosen a more protectionist trade stance. But for Harrison and Hanson (1999) a link between long run growth and more open trade policies is no robust enough since a rise of inequality in incomes appeared in Mexico after a trade reform. Vamvakidis (2002) mentioned that the positive relationship between openness and growth is a recent phenomenon and the domestic trade policy cannot be set independently of the trade policy of the rest of the world. It becomes clear that the environmental sequences of trade are complicated. The production of goods to export or the consumption of goods from imports causes the rise of $CO_2$ emissions in an economy? In China, where the $CO_2$ emissions have almost doubled and it expected to become the biggest polluter over the next years, the exports seems to be the main cause, since there was an increase in production of products that exported to developed countries (Weber et al, 2008). On the contrary, according to Liu et al (2010), in China, household consumption resulted in the growth of $CO_2$ emissions as the consumer's demand for energy intensive products is an important driving force and offset the reduction from technological development in the production process. With trade liberalization, it is hard to distinguish the limits of environmental consequences in the production chain since many products that are used in production process as inputs, have been produced in foreign economies. The predominance of internationally supplied resources and products is the case for USA and Canada, the world's largest trading partners, where production or consumption of goods in one country often exerts significant energy and GHG influences (leakages) on the other (Norman et al, 2007).

Furthermore, a main variable that needs to be considered is energy use. For Stern D (1993) energy use is a factor of economic growth. Richmont and Kaufmann (2006) attempted to discover a turning point of an EKC with the effect of fuel mix (gas, oil, coal, nuclear and others). They conclude in general that energy mix (fossil fuels, nuclear, hydroelectric and others) is important and energy prices should be involved since prices are a significant determinant of energy use. For Agras and Chapman (1999) energy prices are an important indicator of energy demand and consequently carbon dioxide emissions. So, if we control energy use, this will lead to controlling GHG emissions? It seems that the case of energy use does not affect all the countries in the same way as causality from energy to GDP is found to be more prevalent in the developed OECD countries compared to the developing non-OECD countries. That statement implies that a policy to reduce GHG emission through energy consumption reduction is likely to have greater impact on the GDP of the developed rather than the developing world (Chontanawat et al, 2008). Energy dependence combined with energy prices consist a important factor of the final energy use. Asafu-Adjaye (2000), in a study on Asian developing countries, concluded that energy-dependent economies are relatively more vulnerable to energy shocks. The use of renewable energy sources may be a solution to growing energy challenges and energy dependence (Asif and Muneer (2007). The increasing concern about climate change, the depletion of fossil fuel reserves and the

[17] Tertiary (services) sector include: value added in wholesale and retail trade (including hotels and restaurants), transport, and government, financial, professional, and personal services such as education, health care, and real estate services, and bank services (World Bank, see references).

scientific research about the development of cleaner forms of energy make the switch to renewable energy sources quite achievable. Renewable energy resources such as solar, wind, biomass, and wave energy are supposed to be abundant, inexhaustible and more environmentally friendly.

Another critical parameter for an economy is the reserves of energy resources. During the past decades, the paradox of a negative impact of natural resource abundance on economic growth has been widely observed. Many countries rich in oil reserves, gas, or tropical forests used for timber production experienced low growth rates while many resource-poor countries experienced high growth rates. That phenomenon is not global and several exceptions can be found. Sachs and Warner (2001) reports that resource-abundant countries tended to be high-price economies and as a consequence they tended to miss-out an economic growth based on the export of other goods than energy resources. More recently, Papyrakis and Gerlagh (2007) concluded that natural resources wealth may stimulate growth but only under certain conditions; a natural resources economy that suffers from corruption, low investment, protectionist measures, deteriorating terms of trade and low educational standards will probably not benefit from its natural wealth due to adverse indirect effects. So natural resources wealth increases growth, if only negative indirect effects are excluded.

Finally, another two indicators that should be added to our model is income distribution and the percentage of unemployment of an economy. Income per capita as an indicator does not provide any information about economic inequality and the distribution of income across individuals and households. In order to better understand the economic structure of an economy we must take in consideration the gap of income between rich and poor habitants (percentage of people living in poverty, unemployment of workforce) since we expect that if an economy is stamped by high inequalities of income distribution then environmental concerns will not be supported by people.

## 3. Generating a Model

The purpose of this section is to take the first steps in generating a model linking $CO_2$ with the parameters discussed in the previous sections. A basic general function implies that:

$$CO_2 = f(Y, E, G, Cl) \qquad (1)$$

Where the parameters stands for:

$CO_2$ → the level of $CO_2$ emissions produced by an economy

Y → the income level of this economy

E → other economic parameters

G → geographical conditions

Cl → the climate conditions

The general idea of the current study is shown in figure 1.

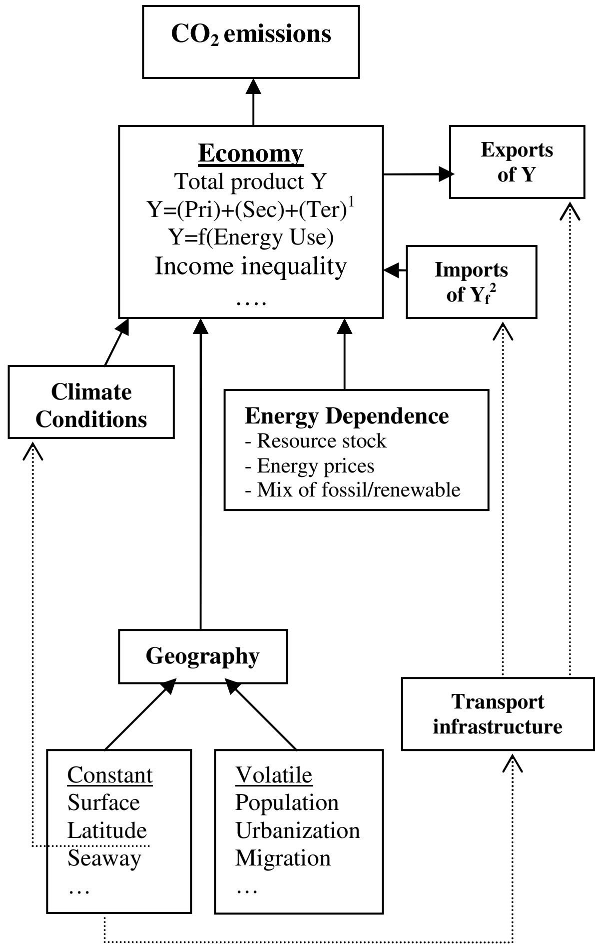

Figure 1: The chain of economic activity and $CO_2$ emissions.

Where:

[1]→ (Pri) is Primary sector (includes agriculture, fishing, forestry, mining, quarrying industries), (Sec) is secondary sector (industry), and (Ter) is tertiary sector (services).

[2]→ $Y_f$ are the products and services imported from foreign countries.

As seen in this figure, many relationships over an economy's activity are set off, that result to the total $CO_2$ emissions which are being generated. Individual and more complex associations will be examined in order to derive the significance and the influence of each component to the other elements of this chain. Of course, several other geographic, climatic and economic parameters will be included in the final model.

Another model that can be applied is to consider and examine the energy consumption. Final energy consumption is the essential path through which $CO_2$ emissions are produced. The relationships that seem to occur are showed in the following figure 2 in a simple basis:

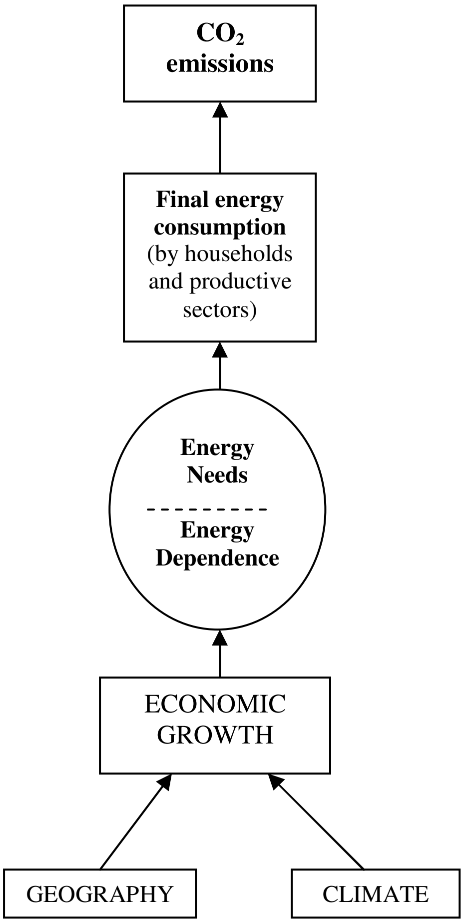


Figure 2: Final energy consumption and $CO_2$ emissions

The models that we develop in this section can be also applied on other gases such as $SO_X$ and $NO_X$. In order to examine the proposed models, countries from European Union and OECD will be selected, although it would be interesting to examine the case of non-OECD countries.

## 4. Conclusions

So far, with the inspection of several parameters that seems to affect the income - environment relationship, it becomes obvious that the income - environment case can not be investigated strictly under the influence of income per capita that is usually used. Additional characteristics that diversify one economy from another should be included in order to describe the $CO_2$ emissions. So, parameters like geography, climate conditions and economic structure must be considered in order to provide a more realistic and generalized image of an economy as a whole. The final target is to propose some more accurate relationships in an attempt to reveal an economy's impact on $CO_2$ emissions.

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# Comparison of the thermal characteristics and temperature profile of the ground in Cyprus with other Mediterranean countries

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## Abstract

The purpose of this study is to record and compare the ground temperatures and other thermal characteristics of the ground at eight representative sites in Cyprus with other studies both in the island and the nearby Mediterranean countries. Paul Morgan in the 1970s measured the geothermal gradient in 33 boreholes in Cyprus. Since then, the thermal behaviour of the ground has not been sufficiently studied and recorded, especially in inhabited areas, resulting in limited information for the design of ground heat exchangers and its effect on the efficiency of Ground Coupled Heat Pumps (GCHPs). As simulation studies indicate the ground temperature is one of the main system parameters that affect the performance of GCHPs. Measurements carried out on the representative locations in Cyprus show that the surface zone reaches a depth of 0.5m. The shallow zone penetrates to 7-8 m and there after the deep zone follows. Also the temperature of the ground at the deep zone has a range between 18-23 °C and is usually higher than that of the ambient air during the cold months of the year and lower during the warm months, showing suitable temperatures for the efficient use of GCHPs. Ground temperatures in Cyprus are lower than those examined in Jordan and higher than the ones in Portugal.

**Keywords:** Geothermal, ground temperatures, ground thermal properties

## 1. Introduction

Studies show that the ground temperature varies with depth. At the surface, the ground is affected by short term weather variations, changing to seasonal variations as the depth increases. At the deeper layers, the ground temperature remains almost constant throughout the seasons and years and is usually higher than that of the ambient air during the cold months of the year and lower during the warm months [1-2]. The ground therefore is divided into: a) the surface zone where hourly variations occur, b) the shallow zone, with monthly variations and c) the deep zone, where the temperature is almost constant.

The structure and physical properties of the soil are factors affecting the temperature, at all zones. The temperature of the ground is a function of its thermal conductivity, density and specific heat, the geothermal gradient and water contend and flow. Studies carried out in several locations in Cyprus show that according to the formation of the ground the surface zone reaches a depth of about 0.5m. The shallow zone penetrates to 7-8 m and there after the deep zone follows. Also the temperature of the ground at the deep zone has a range between 18-23 $^{o}$C [2-5].

Ground Heat Exchangers (GHE) are heat exchangers used for the exploitation of the ground thermal capacity and the difference in temperature between ambient air and ground. They use the ground as a heat source when operating in the heating mode and as a heat sink when operating in the cooling mode, with a fluid, usually air, water or a water–antifreeze mixture, to transfer the heat from or to the ground [5].

It is expected that data collected from areas with climatic and soil characteristics similar to those of Cyprus would be applicable and show similar trends for the case of Cyprus as well. Other Mediterranean countries like south Greece, south Turkey, south Italy and the western areas of Middle East would be expected to be comparable with Cyprus.

As stated by Andritsos et. al. [6] the capacity of geothermal applications installed in Greece in 2000, was 57.13 $MW_{th}$ while by the end of 2008 this number was doubled reaching 115.5 $MW_{th}$. The main reason for this is the increase in use of GCHPs. From the 0.4 $MW_{th}$ installed capacity in 2000 it increased to 40 $MW_{th}$ by the end of 2008. This is due to the fact that GCHPs are also used for cooling. The cooling load in Southern Mediterranean countries is much higher compared to countries of the Central or Northern Europe. This makes the GCHP systems more efficient than the common air cooled heat pumps since they operate in extreme weather conditions during winter and summer period.

However, the thermal behaviour of the ground in Cyprus has not been sufficiently studied. Therefore the information available so far for the design of ground heat exchangers is not representative for the whole of the island and it cannot be compared yet with other countries.

## 2. Geothermal investigation in Cyprus

***Morgan's experiment***

In a geological study, Paul Morgan in the 1970s [7] measured the geothermal gradient of 33 boreholes in Cyprus. The locations of the boreholes are shown in figure 1. A temperature measuring thermistor was mounted in a probe on the end of a four conductor cable and a Wheatstone bridge circuit with 1:1 ratio arms was used to measure the thermistor resistances. The four conductor cable was used to provide automatic compensation for the lead series and insulation leakage resistance contributions from the cable to the measured resistances. In order to measure the borehole temperature two different cables were used. The first one was a 4.5 mm outside diameter and 600 m long cable comprised of six pvc insulated 0.5 mm diameter tinned copper conductors laid around a 7/0.5 mm stainless steel strain member. The second one was a 2.8 mm outside diameter and 600 m long cable comprised of four high density polythene insulated 7/0.5 mm stainless steel cores. When both cables were used to measure a temperature at the same depth in a stable borehole, the results agreed to within 0.01 °C. The temperature measurements were made in air filled and water filled boreholes, the air and water movement was taken into account in the calculations made to compensate possible errors.

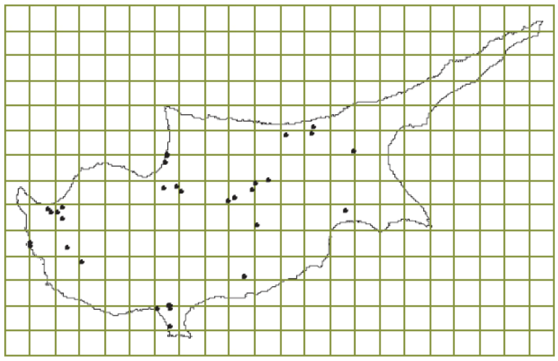

Figure 1: Geological map of Cyprus depicting Morgan's (1973) borehole locations. The map was prepared by the Geological Survey Department of The Ministry of Agriculture and Natural Resources of Cyprus on a 10x10 km grid.

***New project, recent measurements***

Since then, a limited number of studies were carried out in order to investigate the geothermal properties of the ground in Cyprus resulting in almost no further information. A Project funded by the Research Promotion Foundation of Cyprus was undertaken by the Cyprus University of Technology and other collaborators in order to gather and publish such information. Six borehole sites were selected based on their geologic layers, prevailing weather conditions and population density in order to include seaside, inland, semi-mountain and mountainous locations. The drilling sites are located in: Lakatamia, Kivides, Meneou, Agia Napa, Geroskipou and Prodromi near Polis Chrysochous as shown in figure 2. In addition to that, two more existing boreholes drilled in Saittas, representing a mountainous location and Limassol, representing a populated sea-side location, were used for data collection of the project.

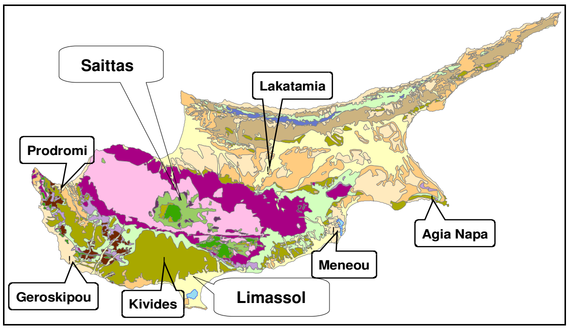


Figure 2: Geological map of Cyprus with borehole locations

A number of U-tube heat exchangers made of polyethylene pipe were installed in the boreholes and were fitted with thermocouple wires at various depths for measuring the ground temperature. All boreholes where filled with bentonitic clay. These combinations enabled the researchers to collect accurate data and conduct a greater number of tests leading to more results and conclusions regarding the earth-heat exchangers.

The Omega thermocouples used are of the K type and are twisted/shielded thermocouple wires ideal for systems sensitive to induced voltages and electrical noise. They are also moisture, abrasion, chemicals and UV light resistant [8]. All the data were recorded using DaqPRO data loggers which were set to record data at 30 minute intervals.

DaqPRO is an eight-channel, compact, stand-alone, portable data acquisition and logging system with built-in analysis functions such as minimum/maximum graph values, the graph average, etc. It is capable for measuring voltage, current, temperature and pulses and it has a variety of selectable ranges for each input. Also, it can be connected to a PC through the DaqLAB software [9].

To check and increase the accuracy of the measurements, the ground temperature at various depths was also measured by using an immersible thermocouple wire connected to an Omega HH41 digital thermometer. The 500 m long thermocouple wire was winded on a small portable spool and immersed in one of the legs of the U-tube heat exchanger which was kept continuously filled with water. While lowering the thermocouple wire the temperature of the water in the tube (and therefore the ground temperature) was recorded at the step intervals were the K-type thermocouple wires were installed. This procedure was done slowly so as to prevent as much as possible the water movement in the GHE.

The results for Lakatamia borehole show that the shallow zone, reaching a depth of up to 8 m, presents seasonal variation and is not affected by the daily ambient air variations as indicated in figure 3. The yearly ground temperature variation at the depth of 0.5 m is within the range of 13.7 °C and 25.8 °C. The temperature presents a lower variation range as the depth increases and at 8 m it varies only slightly in the range of 20.8 °C to 21.3 °C

The rate of how rapidly the temperature in the ground increases at constant heat flow is called the geothermal gradient and is a function of the ground thermal conductivity. The slope of the curves representing the temperature distribution in the ground for that period indicates that the geothermal gradient of the locations under study is between 1 °C to 1.5 °C per 100 m.

Rock samples were collected from individual borehole lithologies during drilling. The collected samples were examined by the Geological Survey Department (GSD) of the Ministry of Agriculture and Natural Resources of the Republic of Cyprus. The ground layers mostly include sandy marls, chalk, limestones and sandstones.

Figure 4 depicts the borehole lithology at the six selected locations as prepared by the GSD. Additionally, samples representing the formation of the boreholes were collected from the nearby areas for analysis. For every sample, a number of thermal conductivity measurements were made using the Hukseflux thermal sensor device.

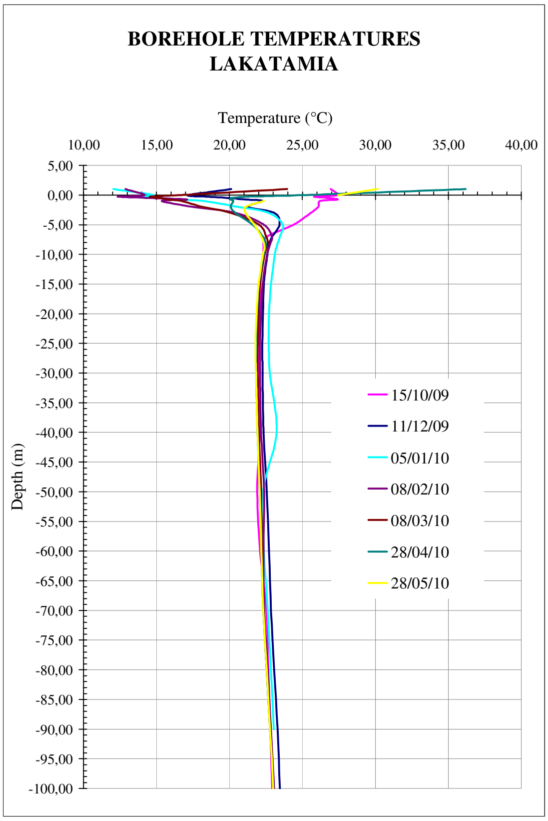


Figure 3: Borehole temperature distribution in Lakatamia for the period of October, 2009 to May, 2010.

The thermal conductivity of every type of the samples is not constant but it varies. The samples examined gave a range of thermal conductivities between 0.6–1.38 W/mK when dry and 0.9–2.15 W/mK when saturated. This is due to the fact that the specific weight of the collected rocks also varies. Samples collected from the surface appear to be less dense than the ones collected from deeper in the ground. Also the amount of saturation with water of every sample in the actual layer of the borehole is another factor for the variation.

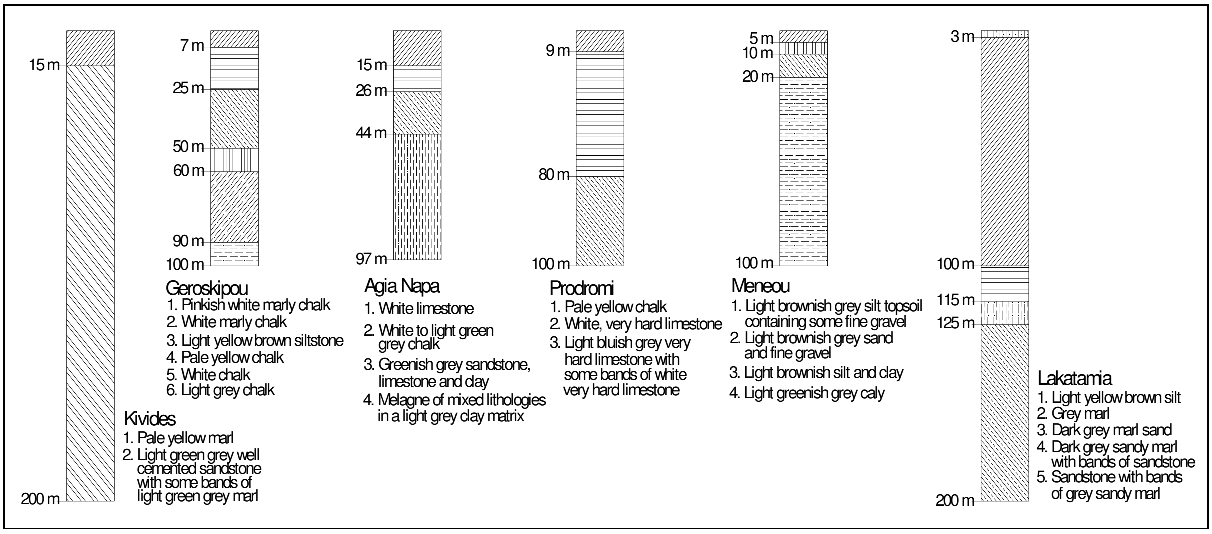


Figure 4: Borehole lithology at the six selected locations.

For every borehole a number of Thermal Response Tests (TRT) were carried out in order to determine the average thermal conductivity of the ground (λ) and the average temperature of undisturbed ground. The line source model, which was used for the analysis of the results, is a method of evaluating the characteristics of the borehole and is the most widely used nowadays [2]. This model is based on the theory describing the response of an infinite line source model and although this model is a simplification of the actual experiment, accurate data for the design of borehole heat exchangers can be obtained on site. The tests were carried out by injecting a constant heat energy into a borehole with known depth and known diameter. The recorded data included the inlet and outlet temperatures of the heat carrier fluid, the flow and the input energy over a certain period, etc. It should be noted that in some boreholes two types of GHE with different diameters were tested. Table 1 lists the obtained results from the TRTs carried out at five of the six data collection locations. Although the lithology of the ground in the eight locations differs, the TRT results showed similarity in the boreholes thermal conductivity. The differences obtained in the results of the TRTs in Geroskipou (1.42 and 1.97 W/mk) and Meneou (1.72 and 1.4 W/mk) is due to the fact that GHEs with different diameter were used. The effect of the diameter of the GHEs on the TRT results is subject to further investigation.

### 3. Comparison of data within Cyprus and other Mediterranean countries

A comparison on the ground temperature distribution recorded in Saittas and Agia Napa against the ground temperature distribution recorded by Morgan in Polemi and Pigi, which are nearby areas to the above two sites, are presented in figure 5. Polemi is a mountainous location in the west site of the island and can be compared to the Saittas borehole. Polemi is also the site where the lower temperatures in the Island were recorded by Morgan. Pigi represents a coastal to inland location in the east site of the island and is the place that Morgan recorded the highest ground temperatures. According to the depicted curve profiles, the ground temperatures recorded by Morgan 39 years ago are very close to the ones recorded recently.

Table 1: Thermal Response Tests results for various locations with a fluid flow of about 14-16 l/min.

| Location | Initial fluid temperature °C | Thermal conductivity λ, W/mk |
|---|---|---|
| Agia Napa | 23.5 | 1.58 |
| Lakatamia | 23 | 1.68 |
| Geroskipou | 24 | 1.42 |
| Geroskipou | 21.5 | 1.97 |
| Meneou | 22 | 1.72 |
| Meneou | 22.3 | 1.40 |
| Prodromi | 24 | 1.87 |

Correira and Safanda [10] reported the ground surface temperature history reconstructed from borehole temperatures. In their study they recorded the temperature distribution and the thermal conductivity of the ground in a 200 m deep borehole located 5 km northwest of the town of Evora in southern Portugal. The place is located in an old cork tree forest with hercynian rock, porphyric granite with about 60% of feldspar and 15% of quartz and muscovite. A non-productive borehole drilled for water supply was cased with a 6.3 cm diameter PVC pipe, grouted at the bottom and filled with water. In this way the convection effects were limited to 0.001 °C resulting to reliable temperature recordings.

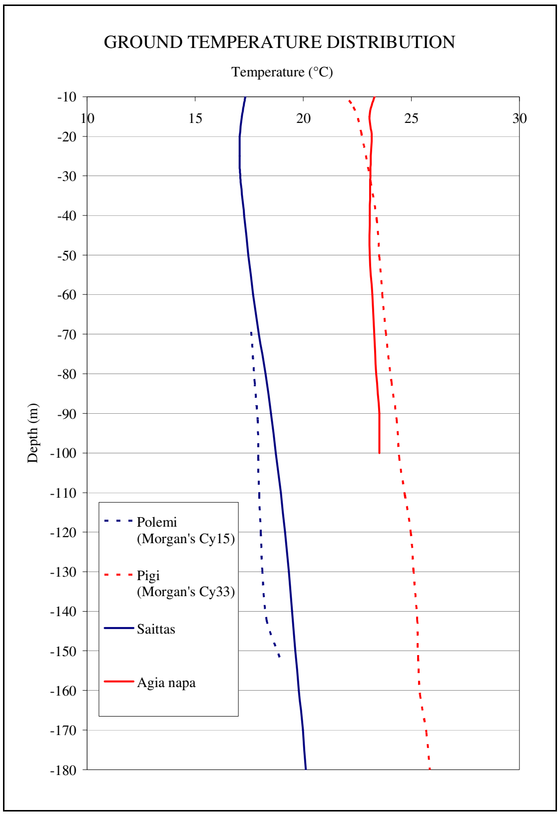


Figure 5: Comparison of the ground temperature range recorded in this project and the study carried out by Morgan for Cyprus.

Similarly, Forster et, al., [11] studied the surface heat flow of the Arabian Shield in southern Jordan (the western part of the Arabian plate). Five non-productive boreholes of up to 900 m deep drilled for the exploration of groundwater were used in the study. The area, also named the Southern Desert, is characterized by a relatively flat land surface and is mainly formed by Paleozoic sediments. The distribution of the ground temperature was recorded in spring 2002 and 2003. The accuracy of the recording process in the liquid filled part was limited to ~0.1 °C while the logs of the air filled parts above the water level in the boreholes were not used.

Table 2 lists the ground temperature range and the thermal conductivity range recorded by the above studies in three countries of the Mediterranean region i.e. Cyprus (two different studies), Portugal and Jordan. In the borehole in Evora, Portugal, the lowest ground temperatures were recorded with about 1 °C difference between highest and lowest values. In the case of Cyprus the lowest ground temperature records are almost the same with the ones recorded in Portugal. The difference is in the highest temperature records that reach the values of 23.2 °C (or 24.2 °C according to Morgan), 4 °C or 5 °C higher than the ones recorded in Portugal. In the case of Jordan, ground temperatures start at about 24.5 °C and reach 31°C, significantly higher than Cyprus.

The mean ambient air temperature in the locations of the boreholes is such so as to urge to the conclusion that the ground temperature distribution in the boreholes would be similar. Actually, it was expected to find lower ground temperatures in Portugal than Cyprus. Similarly higher ground temperatures were expected in Jordan compared to the other two locations. On the contrast, the differences in the ground temperature distribution were lower than the expected ones. The temperatures and thermal conductivities recorded in the boreholes strengthen the statement that the temperature of the ground is affected mostly by the lithology of the ground than the mean ambient air temperature in the area.

Table 2: Thermal properties of the ground up to the depth of 100 m reported in Cyprus, Portugal and Jordan

| Location | Deep zone Temperature range °C | Thermal conductivity range λ, W/mk |
|---|---|---|
| Cyprus | ≈ 18.3 - 23.2 | ≈ 1.40 - 1.97 |
| Cyprus (Morgan's study) | ≈ 18 - 24.2 | ≈ 1.3 - 2.3 |
| Portugal (Town of Evora) | ≈ 18.2 - 19.3 | ≈ 2.8 ± 0.2 |
| Jordan (BH5) | ≈ 26 - 31 | ≈ 1.55 - 5.67 |

| | | |
|---|---|---|
| Jordan (BH9) | ≈ 24.5 - 26 | ≈ 1.55 - 5.67 |

## 4. Further work

One of the main objectives of the project undertaken by the Cyprus University of Technology is the creation of the geothermal map of Cyprus. For this purpose artificial neural networks will be used. These will be trained using the data measured for the boreholes studied. The data base will be enriched by the Geological Department of Cyprus which will provide data for some more boreholes used in other projects. Some of the parameters needed for the training of the network are the mean annual ambient temperature, the type of ground and the temperature of the ground at several depths in the locations. The output will then be used as input to a specialized contour drawing software in order to draw iso-temperature lines.

Detailed information of the geothermal conditions in different locations in the Mediterranean area with similar weather conditions to that of Cyprus might be useful for the evaluation of the artificial neural networks to be developed. Unfortunately, such information is still limited compared to the available information concerning northern countries or areas with cold climates.

## 5. Results and Conclusions

The following results and conclusion can be drawn from the above presentation:

- The deep zone temperature of the ground in Cyprus is constant throughout the year and is within the range of 18.3 °C - 23.2 °C, 5 °C difference between lower and higher recorded temperature. The warmer site is the one in Agia Napa, sea-side area on the southeast of Cyprus, while the coldest is the one in Saittas, mountainous area on the mainland.
- The results of the project undertaken by the Cyprus University of Technology agree with the results of the project carried out by Morgan in 1970's.
- Ground temperatures in the boreholes examined in Jordan are higher than the ones in Cyprus and those in Portugal, as expected.
- The ground temperature distribution in the borehole examined in Portugal has the lowest range than those in Cyprus and Jordan and is about 1 °C. The ground temperature range in Cyprus and Jordan is almost the same and is about 5 °C.
- The lithology of the ground is the most important factor affecting its geothermal characteristics.
- Limited information is available regarding the thermal characteristics of the ground in warm climates and especially the area of the Mediterranean Sea.

## 6. Aknowledgments

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