# LOCAL AIR QUALITY IMPACTS DUE TO DOWNWASH AROUND THERMAL POWER PLANTS: NUMERICAL SIMULATIONS OF THE EFFECT OF BUILDING ORIENTATION

SERPİL KAYIN, GÜRDAL TUNCEL and COȘKUN YURTERI
*Environmental Engineering Department Middle East Technical University, 06531 Ankara, Turkey*
*(* author for correspondence, e-mail: cyurteri@rorqual.cc.metu.edu.tr)*

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**Abstract.** One of the primary adverse environmental impacts associated with power generation facilities and in particular thermal power plants is local air quality. When these plants are operated at inland areas the dry type cooling towers used may significantly increase ambient concentrations of air pollutants due to the building downwash effect. When one or more buildings in the vicinity of a point source interrupt wind flow, an area of turbulence known as a building wake is created. Pollutants emitted from relatively low level sources can be caught in this turbulence affecting their dispersion. In spite of the fact that natural gas-fired combined-cycle power plants have lower air emission levels compared to other power plants using alternative fossil fuel, they can still create significant local air pollution problems. In this paper, local air quality impacts of a natural gas-fired combined-cycle power plant located in a coastal area are compared with those of another natural gas-fired combined-cycle power plant having identical air emissions but located in an inland area taking into account differences in topography and meteorology. Additionally, a series of scenarios for the inland site have been envisaged to illustrate the importance of plant lay-out configurations paying particular attention to the building downwash effect. Model results showed that different geometrical configurations of the stacks and cooling towers will cause remarkable differences in ambient air pollutant concentrations; thus it is concluded that when selecting a plant site, a detailed site-specific investigation should be conducted in order to achieve the least possible ambient air pollution concentrations with the given emissions.

**Keywords:** building downwash effect, natural gas-fired combined-cycle power plants, regulatory air quality modelling

## 1. Introduction

Primary power generation facilities in Turkey are based on hydro and lignite reserves. In recent years, however, imported natural gas has played an increasingly important role in power generation. This trend toward natural gas is driven by economics, environmental concerns and the policy objectives of the Ministry of Energy and Natural Resources. In this study, two sites have been selected for investigation of local air quality impacts originating from natural gas-fired combined-cycle (NGCC) power plants, namely in the Bursa and Tekirdağ regions (see Figure 1) both of which are marked by increasing regional demand for electricity due to intensive industrial activities and dense population. In fact, two NGCC power

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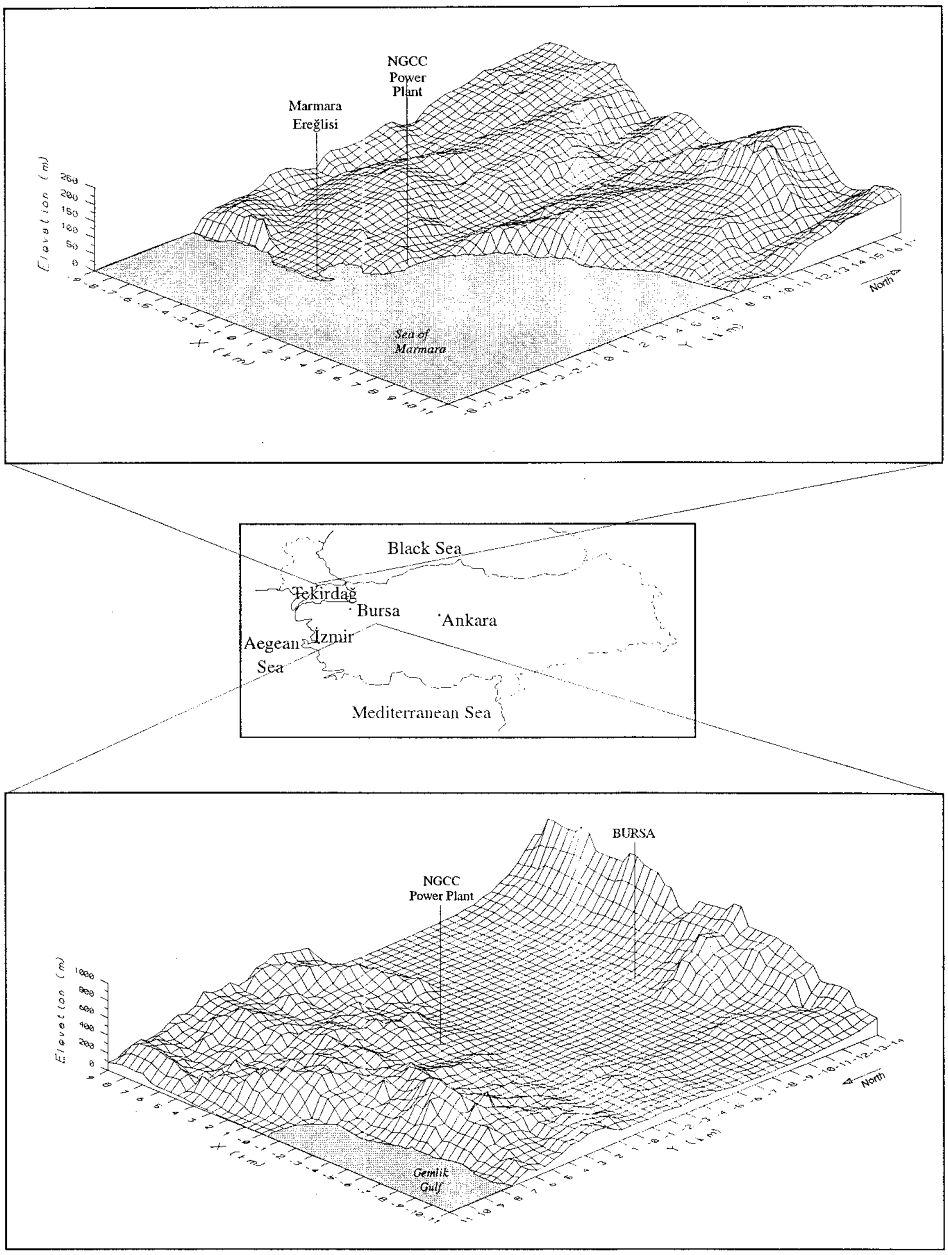

*Figure 1.* Digitized topography of the NGCC plant sites.

plants are currently under construction in Bursa and Tekirdağ. However, in this study, the two plants were assumed to have identical energy production capacities and as a result, the same emission levels, for the sake of comparison.

Potential air quality impacts of a power plant are related to the fossil fuel to be used which determines the technology of choice as well as corresponding mitigation measures and site selection. In this regard, topography, meteorology and ecology of the local environment will play a significant role on the overall impact. However, factors such as transmission losses between the points of production and consumption limit the site selection alternatives. Therefore, production of the energy at the site of need but with the minimum adverse environmental impacts is of utmost importance.

Site selection has further implications in terms of local air quality impacts. For example, the cooling system depends on whether the power plant is located at a coastal or inland area. In coastal areas where the sea water is the cooling medium of choice, thermal discharge into the receiving water body may induce some adverse environmental impacts (Çakıroğlu and Yurteri, 1998). On the other hand, dry or wet cooling towers may be used at inland locations where a sufficient supply of cooling water is not available. Operation of the power plants at inland areas requiring the dry type cooling tower[1] may significantly increase ambient pollutant concentrations due to building downwash (Kayin *et al*., 1995).

Prior to site selection and construction of a proposed power plant, the primary analytical tool to estimate potential air quality impacts is the use of modelling techniques (Kuntasal and Kayin, 1995). In this study, air quality impacts of NGCC power plants having much lower air emission levels[2] compared to other fossil fuel alternatives have been investigated in different topographical and meteorological settings via modelling studies. In addition, the effects of different plant lay-outs on local air quality impacts have been illustrated with a series of scenarios having different geometrical configurations, paying special attention to building downwash.

## 2. The Building Downwash Effect

The building downwash effect is induced by tall buildings adjacent to stacks as well as by topography (Huber and Synder, 1976; Huber, 1977; Huber and Synder, 1982). In general, the magnitude of the building downwash effect is mainly determined by i) the height difference and distance between the stacks and adjacent buildings,

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[1] In this type of cooling tower, warm water is circulated through the walls of a hollow parabolic structure through which air is blown. Since the specific heat of air is much lower than that of water, the amount of air required to be blown through the tower is rather large resulting in the necessity of construction of large and tall cooling towers.

[2] In addition to natural gas being a cleaner fossil fuel, higher thermal efficiencies are achieved in NGCC power plants compared to conventional coal-fired thermal power plants. Thus, carbon monoxide (CO) emissions per unit of electricity energy produced will be substantially lower, and suspended particulate matter (SPM) emissions will be very low, and sulphur oxides ($SO_x$) emissions will be zero or negligible. Also nitrogen oxides ($NO_x$) emissions can easily be minimised by the use of $NO_x$ burners.

ii) exit gas temperature and velocity, and iii) frequency of occurrence and speed of winds blowing from the stacks to the buildings.

Occurrence of downwash is common even with small emissions and may greatly increase ground level concentrations (GLCs) in the immediate vicinity downwind of the source. Similarly, if the efflux velocity is too low, the stack is too short or the emission is denser than air, the pollutant plume may be brought to the ground very near the source. Downwash due to terrain or nearby tall and large buildings is also possible. If the effluent is emitted from a stack or vent on or near a building, it may be brought downward by the flow of air over and around the building.

In the case of thermal power plants where efflux velocity and exit temperature of flue gas are quite high, occurrence, intensity and frequency of the downwash mainly depend on the wind blowing from the source towards the obstacles; therefore, geometries of the stacks relative to the obstructing buildings is of significant importance. Thermal power plants located at inland areas which are equipped with dry type cooling towers may induce pollution episodes in the vicinity of the source which may persist from a few hours to days depending on the meteorological factors, hence resulting in the oscitancy of short-term (hourly and daily) air quality standards. In this regard, taking into account long-term average wind pattern standards and arranging the plant lay-out accordingly would only help reducing long-term (annual) average GLCs. However, in order to minimize short-term GLCs, a series of other measures may have to be taken. This study concentrates on the importance of the building downwash effect on local short-term air quality impacts and illustrates ways of efficiently reducing the intensity of this phenomenon.

## 3. Modelling Approach

In this study, short-term and long-term GLCs of pollutants originating from two NGCC power plants located at different sites with identical atmospheric emissions have been analyzed by using the Industrial Source Complex-Short Term (ISCST3) model developed and approved for regulatory use by the U.S. Environmental Protection Agency (1995).

The ISC model has undergone several revisions to correct and improve its technical features (U.S. EPA, 1987a, 1992) since first being issued (Bowers, *et al.*, 1979) and various publications have discussed applications and verifications of the model (e.g. Bowers and Anderson, 1981; Bowers *et al.*, 1982; Baumann and Dehart, 1988). The model currently includes a revised building downwash treatment with an extension of the direction-specific treatment based on the suggestions of Scire and Schulman (1980), Schulman *et al.* (1985), Schulman and Hanna (1986). U.S. EPA maintains a Guideline on Air Quality Models which provides the agency's guidance on regulatory applicability of air quality dispersion models in general (U.S. EPA, 1987b). Since the ISC models include a wide range of options for modelling air quality impacts of pollution sources, it makes them popular choices among the modelling community for a variety of applications (Touma *et al*., 1995; Rorex, 1990).

The ISCST3 model is considered to be one of the most advanced computer models that can estimate hourly, daily and annual average GLC values or concentrations at elevated points under varying conditions of real-time meteorology. Being mainly a Gaussian diffusion model, it also combines and enhances various dispersion model algorithms to account for pollutant sources such as isolated stacks and fugitive emissions. In assessing the air quality impact of emissions from a wide variety of sources associated with an industrial source complex, the model also considers wake effects, gravitational settling, and dry and wet deposition. Point, volume, area or open pit sources can be modeled with ISCST3. The model has an option to consider the effects of aerodynamic wakes and eddies produced by on and off-site buildings and structures. Additionally, the model has a terrain correction option. The model requires three types of input data: i) receptor data including coordinates and elevations of selected grid points and receptors, ii) meteorological input including hourly data for wind direction and speed, ambient air temperature, Pasquill stability class, mixing height, wind profile exponent (optional), and vertical potential temperature gradient (optional), and iii) source data requiring source location with respect to a user-defined origin, source elevation, source diameter, exit velocity, exit temperature and pollution emission rate.

In this study, prior to the ISCST3 Model runs, the Good Engineering Practice (GEP) software (U.S. EPA, 1986) was used to calculate the wind direction specific building heights and widths with respect to the sources, based on 36 wind sectors. Subsequently, the results have been incorporated into the ISCST3 model in order to account for the building downwash effect due to the nearby buildings.

Receptor Data Input: Two rectangular grid systems having the hypothetical NGCC power plants at the origins were prepared for the modelling studies. Both grid systems cover an area of 20 km (East-West) by 25 km (North-South) and each grid square is 500 m by 500 m. The topographical maps showing the borders of the receptor grid systems are shown in Figure 1 for both the coastal and the inland sites.

Meteorological Data Input: A meteorological pre-processor (REG-308, 1990) was used in order to calculate the mixing height and the corresponding Pasquill stability class at each hour. For both sites, model runs were executed for a full year using the 1992 Tekirdağ meteorological data for the coastal site and Bursa for the inland site. Annual wind roses for the year 1992 are shown in Figures 2a and b for Tekirdağ and Bursa Meteorological Stations, respectively. For both cases, a comparison of 1992 data with long-term averages (1929–1979) proved that the selected year of meteorological data represents the general meteorological characteristics of the two regions.

Source Data Input: Table I shows the emission rates and source parameters used in the model calculations for an NGCC power plant having a power generating

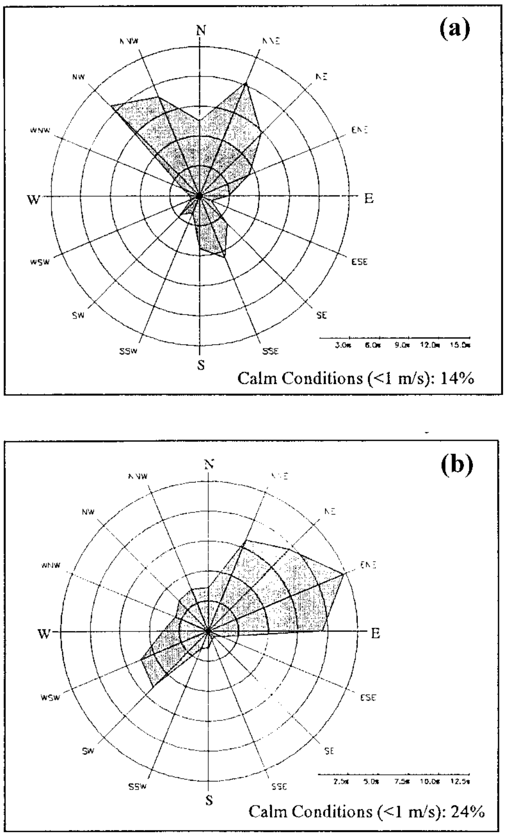

*Figure 2.* (a) Annual wind rose for 1992 for the coastal Tekirdağ Meteorological Station. (b) Annual wind rose for 1992 for the inland Bursa Meteorological Station.

capacity of 1400 MW which consists of two combined-cycle blocks having two stacks each. Figures 3a and b illustrate the lay-out of major on-site structures and buildings included in the GEP runs for both sites. Emission rates[1], lay-outs and dimension of the buildings and cooling towers of the plants are realistic having been adopted from feasibility studies taking into account technical requirements of both facilities[2].

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[1] Modelling studies mainly focused on the emissions of $NO_x$ since the results of preliminary screening runs have indicated that there is no possibility of violating ambient SPM and CO standards.

[2] The height and the diameter of the cooling towers are taken as 135 and 120 m, respectively, at the inland site and the plant has been arbitrarily set along the East-West axis as shown in Figure 3b. In both plants the stack heights are taken as 35 m as this is the calculated minimum stack height requirement according to the currently effective Turkish Air Quality Regulation taking into account exit gas temperature, stack diameter, volumetric flow rate and stack gas pollutant concentrations.

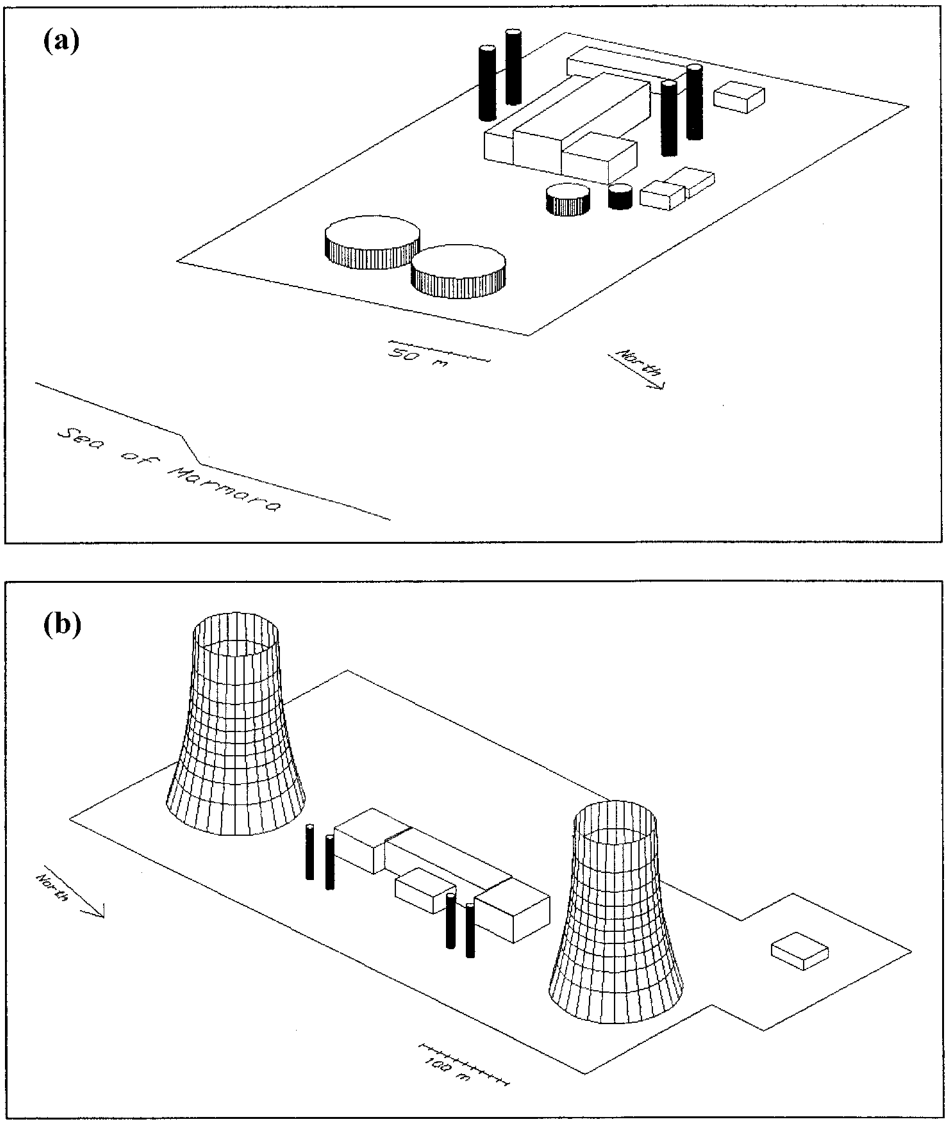

*Figure 3.* (a) Lay-out of on-site structures included in the GEP calculations for the coastal NGCC power plant. (b) Lay-out of on-site structures included in the GEP calculations for the inland NGCC power plant.

## 4. Scenarios of Choice

Two main scenarios were envisaged regarding the site selection for the comparison of air quality impacts of the two NGCC power plants with identical atmospheric emissions: i) one year continuous operation of the coastal Tekirdağ NGCC power plant with a once-through cooling system (see Figure 3a) and ii) one year contin-

TABLE I

Source input parameters used in dispersion modelling

| Emissions[a] | Stack parameters[b] | | |
|---|---|---|---|
| $NO_x$ (g/s) | Diameter (m) | Exit velocity (m/s) | Exit temperature (°C) |
| 112 | 7.11 | 15 | 100 |

[a] Total value for 4 stacks.

[b] Four identical stacks of varying height for different scenarios.

uous operation of the inland Bursa NGCC power plant with two dry type cooling towers (see Figure 3b).

Results of the preliminary runs have indicated that at the inland site due to the building downwash effect caused by the existence of cooling towers, ambient pollutant concentrations are high. Thus, further model simulations have been made in order to illustrate that the building downwash effect is of importance and hypothetical changes in the plant lay-out taking into account the wind direction, stack height and the distance between stacks and the obstacles (i.e. cooling towers) would bring about significant improvements on the local air quality impacts. In this regard, a more detailed investigation has been made regarding: i) the wind sector axes on which the NGCC power plant may be set, ii) different stack heights, and iii) different distances between the stacks and the cooling towers.

## 5. Model Estimations

For the scenarios of choice, model computations were based on the design characteristics of the flue gas given in Table I, topographical settings given in Figure 1, hourly meteorological data of Tekirdağ and Bursa Stations and plant lay-out configurations given in Figure 3. For each scenario, hourly, daily and annual average concentrations of $NO_x$ have been calculated at each receptor point and the maxima were noted including the time and place of occurrence. The model results are outlined below, focusing mainly on maximum concentrations since these are the most significant as far as the regulatory standards are concerned.

### 5.1. EFFECT OF THE EXISTENCE OF COOLING TOWERS

For the coastal site, throughout the receptor domain, estimated annual average ambient $NO_x$ concentrations are very low as shown in Figure 4a. The maximum annual average GLC occur at the far north end of the receptor domain (being only around 1 $\mu$g m$^{-3}$), reflecting the topographical situation causing a tunnelling effect. Additionally, to the southeast of the NGCC power plant some high GLCs exist

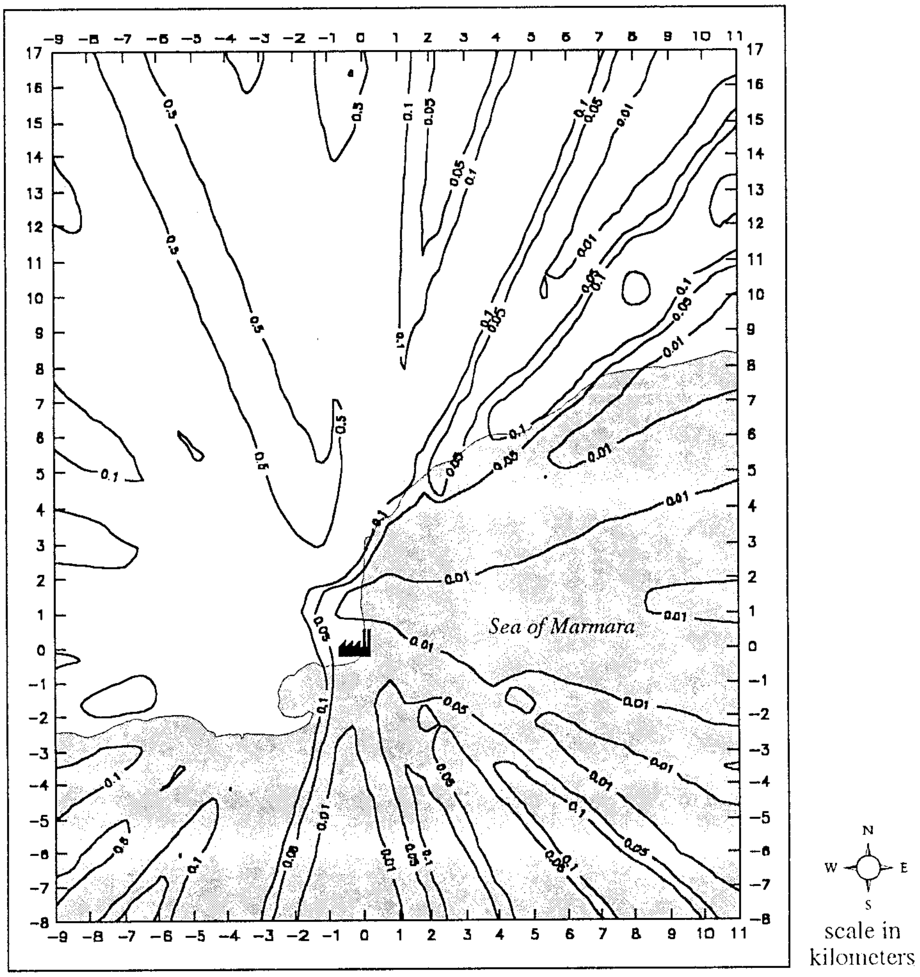

*Figure 4a.* Annual average GLCs of $NO_x$ predicted for the coastal site.

indicating the dominant wind direction observed in the area. Consistent with these annual results, the simulation produced quite low maximum short-term GLCs of $NO_x$, both hourly (~88 $\mu$g m$^{-3}$) and daily (~18 $\mu$g m$^{-3}$) which are substantially lower than the corresponding regulatory standards[1]. On the other hand, simulations for the inland site resulted in markedly high annual average $NO_x$ GLCs (see Figure 4b). The maximum annual average GLC (~85 $\mu$g m$^{-3}$) occurs in the vicinity of the plant site, due to the huge cooling towers which induce building downwash. Consistent with the yearly averages, simulation produced very high daily average (~460 $\mu$g m$^{-3}$) and dangerously high hourly (~3200 $\mu$g m$^{-3}$) maxima, again

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[1] According to the currently effective Turkish Air Quality Standards, the maximum allowable daily and annual average $NO_x$ (as $NO_2$) concentrations are 300 and 100 $\mu$g m$^{-3}$, respectively, for industrial zones. There is no reference value corresponding to the hourly maximum.

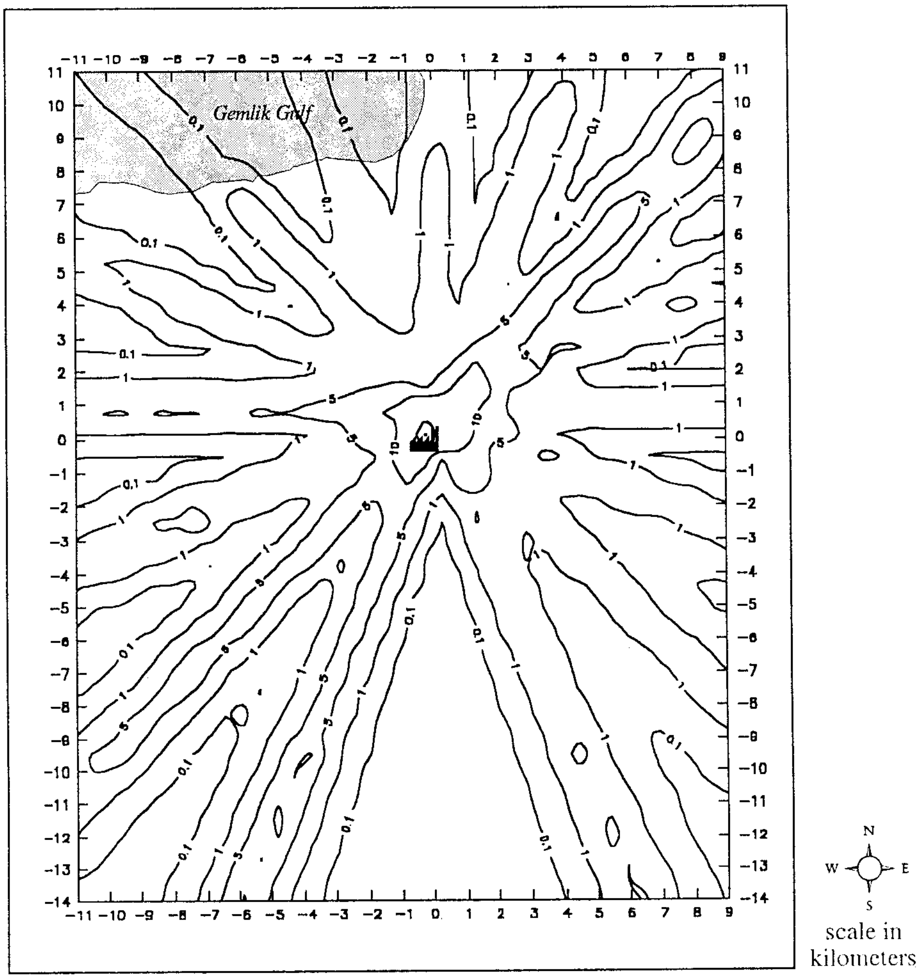

*Figure 4b.* Annual average GLCs of $NO_x$ predicted for the inland site.

in the vicinity of the plant site. In order to illustrate that the high concentrations occurring in the inland area are purely due to the effect of building downwash, an additional simulation was made, keeping all parameters the same, except building downwash. The results obtained from this additional run showed that the GLCs would have been almost as low as in the coastal scenario if there were no cooling towers (maximum annual average GLC: $\sim 140$ $\mu$g $m^{-3}$, maximum daily average GLC: $\sim 40$ $\mu$g $m^{-3}$ and maximum hourly GLC: 5 $\mu$g $m^{-3}$), and thus no building downwash effect. Therefore, the remarkably high GLCs are due to the effect of downwash. Geometries of the buildings, wind direction to carry the pollutants from stacks to the cooling towers, and the frequency of this occurrence determine the overall magnitude of the phenomenon.

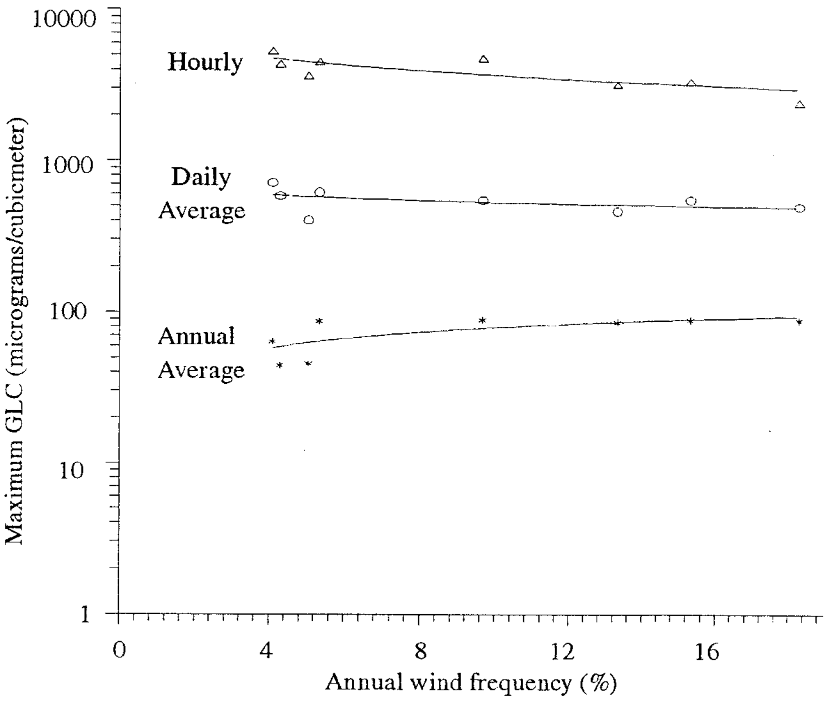

*Figure 5.* Effect of annual wind frequency on maximum GLCs.

In order to decide a plant lay-out which would provide the least possible ambient pollutant concentrations for the given site-specific meteorological and topographical data, a series of model simulations have been made. For this purpose, the orientation of the inland plant has been laid out along different wind sector axes.

### 5.2. EFFECT OF ANNUAL WIND FREQUENCIES (FROM SOURCE TO OBSTACLES)

As expected, long-term average GLCs are quite sensitive to the percent annual wind frequency (see Figure 5) blowing from the stacks to the cooling towers. Maximum annual average GLCs increase from 60 $\mu$g m$^{-3}$ to over 100 $\mu$g m$^{-3}$ with an increase in such annual wind frequencies from 4 to 16%. On the other hand, model simulations clearly indicate that by taking into account only the dominant wind direction and thus selecting the plant orientation which would allow the plumes to blow from the sources to obstacles during the least amount of time within a year would lower long-term averages but not the short-term values. Obviously, the reason for this behaviour is that the number of occurrences of building downwash is limited by the annual wind frequency blowing from the sources to the obstacles, therefore lowering the annual average GLCs. Nevertheless, when building

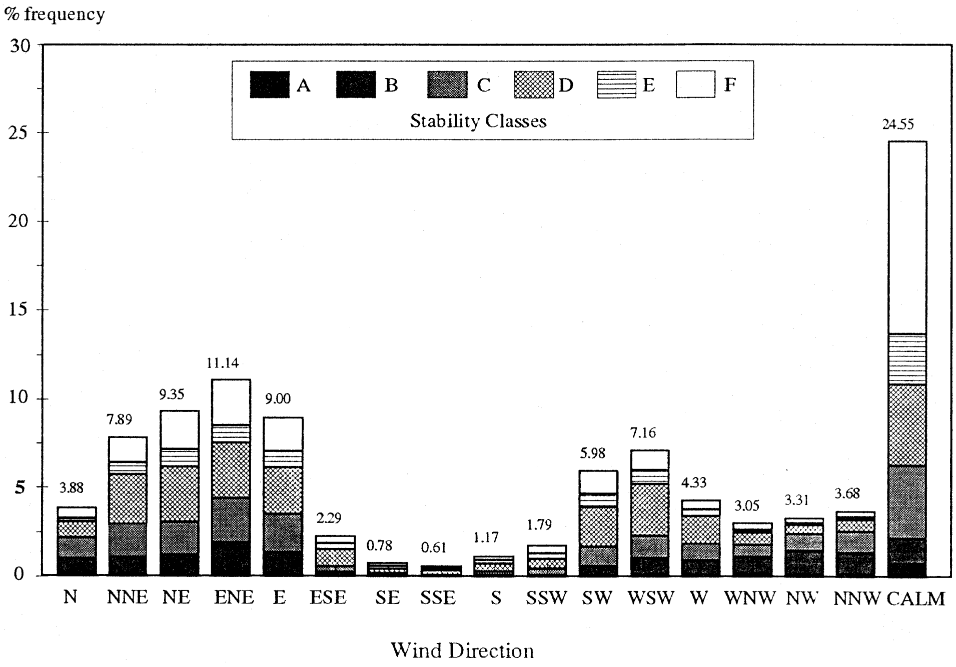

*Figure 6.* Frequency distribution of stability classes by wind direction at the inland Bursa Meteorological Station.

downwash occurs, the intensity of the effect and hence the maximum short-term concentrations created can not be reduced.

Slight fluctuations of the estimated values are purely due to the fact that concentrations are not only the function of wind frequency but also the stability class and hence the mixing height. As shown in Figure 6, the frequency distribution of stability classes by wind direction shows variations and hence affect the estimated concentrations.

### 5.3. EFFECT OF SOURCE HEIGHT

Another way to reduce ambient pollutant concentrations would be to increase the source height so that emission plumes can travel relatively freely without encountering obstacles and thus not being caught in building downwash. Figure 7 shows the effect of stack height on estimated maximum GLCs for plant lay-out settings on different axes. A significant reduction in maximum short-term values is shown at all axes settings, approximately an order of magnitude by increasing stack height from 35 to 200 m, and a greater reduction in maximum annual averages. Increasing the source height obviously enhances the chance of a pollutant plume being captured only partially or passing over the obstacles without any interference; this behaviour is particularly significant when the stack height is higher than 135 m, which is the height of the cooling towers in this study.

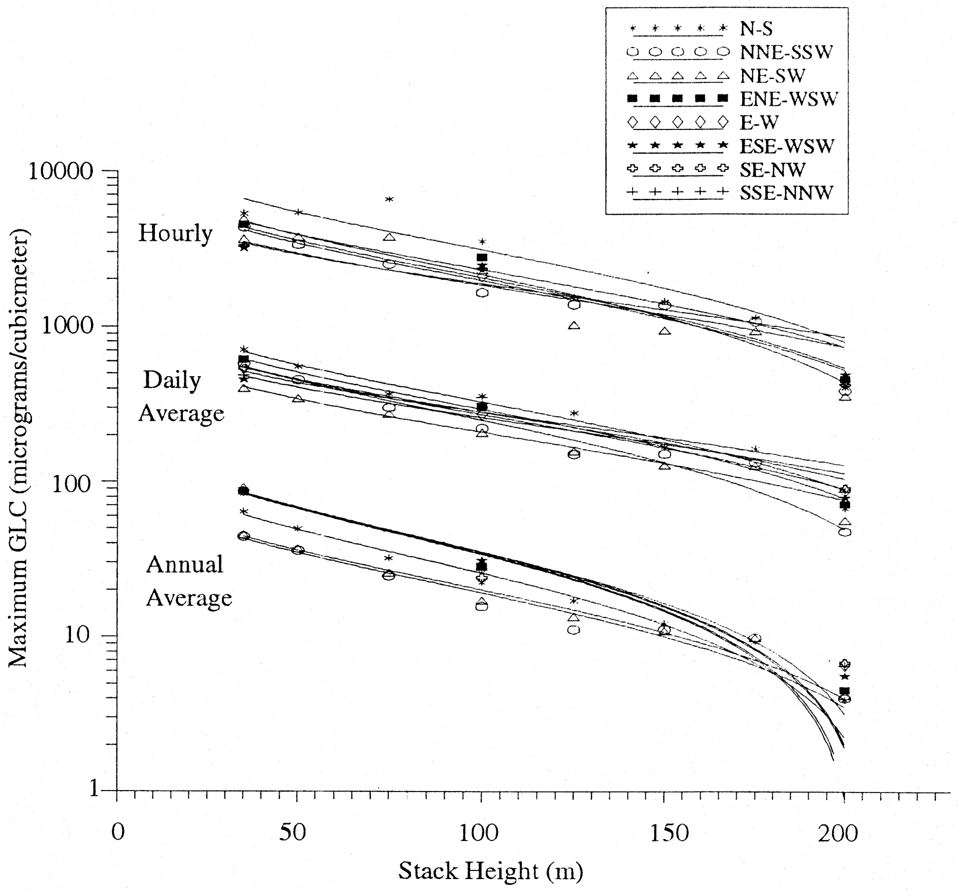

*Figure 7.* Effect of stack height on maximum GLCs for plant lay-out settings on different wind sector axes.

## 5.4. EFFECT OF DISTANCE BETWEEN SOURCES AND OBSTACLES

Increasing the distance between sources and obstacles may significantly reduce the intensity of the building downwash effect since there will be a better chance for plume rise before encountering the obstacles. Figure 8 shows the effect of increased distance between sources and obstacles on estimated maximum GLCs for plant lay-out settings on different axes for two different stack heights: 35 and 100 m. As can be seen from the figure, especially beyond a distance of 450 m, the reduction in estimated concentrations is very significant. In fact, GEP calculations consider a rectangular influence area (5L × 2L × 1/2L)[1] for each building obstacle, and stacks more than 5L distant from a structure are excluded. In this study, according to the model estimations, if a distance scale of more than 450 m between sources

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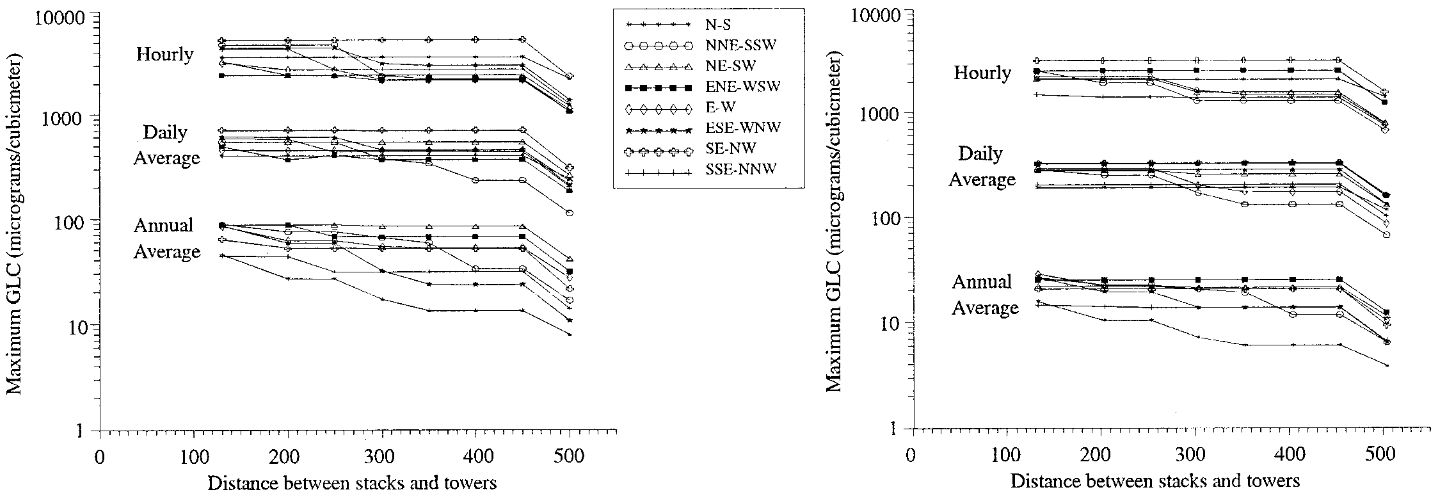
[1] 5L downwind, 2L upwind and 1/2L crosswind distance where L is the lesser of the height or the projected width of a structure.



a) 35 m stack height

b) 100 m stack height

*Figure 8.* Effect of distance between sources and obstacles on GLCs for different plant lay-out settings on different wind sector axes.

and obstacles is allowed, maximum concentrations occur far from the obstacles indicating elimination of a building downwash effect altogether.

## 6. Concluding Remarks

The results of the modelling studies for the two NGCC power plants with hypothetically identical emissions located at different sites with different cooling systems, in turn with different geometrical configurations, revealed that the local air quality impacts are significantly different. A comparison of the model results with the standards stipulated by the Turkish Air Quality Regulation, especially concerning short-term values, shows the importance of downwash, which is pronounced when there is a tall structure near the pollution source.

This study illustrated a viable method to reduce local short-term ambient pollutant concentrations. In parallel with this approach, economical factors such as cost of higher stack and additional land use can be included for optimisation purposes.

Potential adverse environmental impacts of an NGCC power plant located at a coastal site where the cooling medium of choice is sea water, may be significant on the marine environment as a result of thermal discharges. On the other hand, NGCC power plants located at an inland site with a dry type cooling system can be highly significant in terms of local air quality. In order to minimize intensity and frequency, or in other words, the overall effect of building downwash, simple considerations such as increasing the height and distance difference between the stacks and cooling towers, and taking into account the frequency of winds blowing from the emission source to obstacles can be very successful. In fact, a substantial number of combinations regarding the plant lay-out configurations could be tried. In light of this study, therefore, it is concluded that based on site-specific meteorological and topographical data, a detailed modelling investigation endeavouring to determine the lowest possible ambient air pollution concentrations should be conducted for most industrial installations. However, when assessing the results of this study, it should be kept in mind that hypothetical site selection, or in particular plant lay-out configurations, are envisaged from the perspective of local air quality impacts only, despite other concerns such as geography, geology and soil stability which could limit site selection alternatives considerably.

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