Numerical evaluation of urban green space scenarios effects on gaseous air pollutants in Tehran Metropolis based on WRF-Chem model

Somayeh Arghavani a, Hossein Malakooti a,∗, Abbasali Aliakbari Bidokhti b

a Department of Marine and Atmospheric Science (non-Biologic), Faculty of Marine Science and Technology, University of Hormozgan, Bandar Abbas, Iran
b Department of Space Physics, Institute of Geophysics, University of Tehran, Tehran, Iran

ARTICLE INFO

Keywords:
Gaseous air pollutants
Urban green scenarios
Green roof
Dry deposition
WRF/Chem/SLUCM
Tehran metropolis

ABSTRACT

Although positive environmental aspects of increasing urban vegetative spaces are undeniable, using predefined or unmanaged long-term green programs may cause undesirable and unexpected impacts on the air quality in megacities. In this study, the mitigation potential of three green spaces development scenarios (expansion of surface vegetative area, Green Roof development and combination of surface and roof greenery) on three gaseous air pollutants (O3, SO2 and NO2) concentrations in Tehran Metropolis in an early summertime period is analyzed using coupled Weather Research and Forecasting model with chemistry (WRF/Chem), single-layer urban canopy model (SLUCM) and biogenic emission from Model of Emissions of Gases and Aerosols from Nature (MEGAN). Current results indicate that general patterns of diurnal distribution of SO2 and NO2 are totally controlled by the location of anthropogenic sources of pollutants in the south and the city center, beside the prevailing wind field over the city of Tehran. Ozone distribution follows the diurnal advection from the northern and eastern sub-urban areas and distribution of primary pollutants such as NO2. By conducting green scenarios, reduction in the wind speed, variations in pollutants dry deposition velocities which are directly affected by the boundary layer and surface properties, and pollutants deposition fluxes are observed. Alterations in deposition fluxes are not uniform across the city area and clearly conform to changes in pollutants concentrations. In addition, the shallower (deeper) boundary layer height and the buoyancy forcing due to the reduction (increase) in near-surface air temperature cause less (more) vertical mass transport during the day (night), which in both situations could have negative impacts on the air quality since under lower wind speed condition and less convective upward transfer, polluted air near the surface can be trapped. The defined scenarios have shown different impacts over the city of Tehran with the complex urban morphology so, suggestion of the most efficient summertime green policy with the minimum negative feedbacks is not conceivable.

1. Introduction

Living in an urban area increases vulnerability to substantial heat and pollution exposure for both urban residents and other ecosystems. According to the World Health Organization’s report, nearly seven million premature deaths per year throughout the world occur due to urban air pollution (WHO, 2014). Particulate matter (PM10 and PM2.5), sulphur dioxide (SO2), ground-level ozone (O3), nitrogen dioxide (NO2) and carbon monoxide (CO) are the most common urban air pollutants which cause health problems such as chronic obstructive pulmonary and cardiovascular diseases and asthma (Lovasi et al., 2008; Shah and Balkhair, 2011).

Urban Green Structures (UGSs) such as parks, hedges, green roofs and green walls as well as urban green belts are one of the most proposed mitigation measures which can affect both Urban Heat Island (UHI) phenomenon through shading and evapotranspiration processes (Akhari et al., 2001; Georgescu et al., 2014; Oke et al., 1989; Taha, 1997) and local air quality by influencing pollutant deposition (Baumgardner et al., 2012; Escobedo and Nowak, 2009; Petroff et al., 2008; Speak et al., 2012; Vijayaraghavan, 2016; Yang et al., 2008) and dispersion (Janhäll, 2015; Oke, 1987; Wania et al., 2012; Xia et al., 2014).

Plants are natural filters for air pollution which directly uptake pollutants by leaves stomata. Large surface area of plants extends the probability of deposition compared with the other urban surfaces. Deposition rate depends on many factors such as vegetation characteristics (vegetation density and porosity, leaf area index, type of trees, shape and properties of leaves), concentration and size of surface...
pollutants and wind speed (Janhäll, 2015). Another important factor is the proximity of vegetation to the pollution source which directly enhances the deposition rate and lessens the dispersion of pollutants to the nearby environment (Pugh et al., 2012).

On the other hand, trees and other green structures in built-up environments act like living barriers which decrease wind speed, natural ventilation, atmospheric dispersion and vertical mixing (at low wind speeds) which could have deteriorating impacts on air pollution concentration in the urban canopy (Abhijith et al., 2017; Jeanjean et al., 2017; Vos et al., 2013). In a research by Salmond et al. (2013), the influence of urban green spaces on the horizontal and vertical distributions of pollutants in a street canyon is explored. This field study shows that street vegetation reduces upwards physical transport of vehicle emissions and downward flux of clean air, indicating the importance of atmospheric dispersion patterns in the level of air pollution across the urban canopies (Salmond et al., 2013). Giometto et al. (2017) in their field study investigate the performance of trees on mean wind, turbulence and momentum exchange in a real urban canopy. Their research shows that trees are effective momentum sinks for air flows. Reduction in wind speed and vertical turbulent transport is also observed in their research findings (Giometto et al., 2017). Meanwhile, Grundström and Pleijel (2014) suggest that the increased surface roughness in the present of trees causes more shear forcing and turbulence. Their field study also show that the urban vegetation impact on air pollution concentrations is rather small for O$_3$ and NO$_2$ (Grundström and Pleijel, 2014). Numerical simulation by WRF-Chem model also shows that the cooling performance of parks causes reduction in daytime turbulence and shallower boundary layer which leads to the increase in the pollutants concentrations near the surface (Fallmann et al., 2016).

Researches also showed that, as parts of UGSs, green roofs could alter wind field and planetary boundary layer (PBL) structure. For example, findings from numerical simulations, using WRF model indicate that green roofs can reduce horizontal and vertical wind speeds and alter vertical mixing, the time evolution of PBLH, and magnitude of convective processes across the city (Sharma et al., 2016). In another study, Baik et al. (2012) demonstrate that roof greening improves air quality near roads. They show that cool air near the roof flows into the canopy, and enhanced the ventilation and dilution of polluted air (Baik et al., 2012).

Biogenic Volatile Organic Compounds (BVOCs) emissions from plants by participating in photochemical processes also could adversely deteriorate the level of surface secondary air gaseous pollutants and secondary organic aerosols. Previous studies prove that BVOCs are more reactive than anthropogenic VOCs (Atkinson, 2002). Biogenic trace gases such as isoprene directly affect ozone concentration by interaction with nitrogen oxides, while monoterpene and sesquiterpenes affect PM production in hot summer days. Specially, in mid-latitudes climates with high air temperatures and low level precipitations, these interactions are more significant (Calfapietra et al., 2013; Carter, 1994; Churkina et al., 2017; Seco et al., 2007; Seinfeld and Pandis, 2006). Secondary organic aerosols can also alter the radiative balance of the atmosphere which directly influences the boundary layer structure and global climate changes (Claeys et al., 2004; Sun and Ariya, 2006).

Therefore, before the implementation of green mitigating measures at the local scale, diverse aspects of the interaction between UGSs and urban environment should be taken into account since these programs are not temporal and cannot be easily replaced in short-term. Furthermore, the mitigation scenarios should be selected according to the type of predominant pollutants in the area, the location of the pollution sources, patterns of emissions, and meteorological, climatic and geographical characteristics of the region, in order to have the most optimal operations; so generalization of the local findings to other cities is not recommended.

Using meteorological and chemical meso-scale numerical modeling approaches is a common way to predict these effects through simulation of different green scenarios over specified urban areas which is essential for the urban plans design management.

In this study, we explore different UGSs functions in deduction of air pollution and enhancing dry deposition processes using coupled on-line meteorology/chemistry numerical model, WRF-Chem, in Tehran Metropolis (TM). While few studies only investigate the interaction between local climate and air quality for this city (Bidokhti et al., 2016), regarding the new concerns about the development of green spaces and green infrastructures such as the green roof over Tehran, current comparative analyses will investigate the details of feedbacks between green spaces, urban morphology, and local weather and air quality in Tehran for the first time. Through the numerical assessment of the advantages and disadvantages of green scenarios from air pollution abatement point of view, the results of this study will clearly reveal that to what extent the development and management of green structures can be used as a long-term and economic solution for the air quality improvement in this metropolitan.

2. Methodology

2.1. An overview of the study area

Tehran, the capital of IRAN, with the area of ~700 km$^2$, is the most densely populated city in the north of the country (Fig. 1a). TM is surrounded by the Alborz Mountains from the north and northeast, and Dush-E-Kavir on the southern boundary (Fig. 2b.). Due to the large meridional and zonal extent of the city and differences in topographic height, the local climate of Tehran varies from north to south. The difference in the air temperature reaches up to 3 °C, with an annual precipitation of 422.2 mm and 233.4 mm in the north and south parts, respectively. The annual mean temperature changes between 15 °C to 18 °C, and it experiences an annual average rainfall of near 268 mm/year (Alizadeh-Choobari et al., 2016b).

The geographical situation of Tehran controls diurnal wind directions. Southwesterly and northwesterly winds are predominant wind directions in the day and night, respectively, which has a deteriorating effect on TM air pollution issues since it can transfer polluted air from the surrounded commercial areas or dust sources into the city, especially in the daytime. Northern mountains can also induce mountain winds that alternate in direction between night time (northerly katabatic) and day time (southerly anabatic) (Bidokhti et al., 2016).

Tehran also suffers from high levels of urban heat island (Alizadeh-Choobari et al., 2016b; Sodoudi et al., 2014) and air pollution (Alizadeh-Choobari et al., 2016a; Malakooti and Bidokhti, 2014; Mohammadiha et al., 2018; Shahbazi et al., 2016a, 2016b). High level of population growth, the rapid rate of vehicle ownership and high vehicle fleet age are the other important problems (Delkash and Mir, 2016). The phenomenon of dust and suspended particles has also exacerbated the severity of the air pollution problem in recent years. The annual pollution mortality and morbidity damaging costs in the metropolitan area of Tehran is estimated at USD $ 2.6 billion which considers human health effects and underestimates the total economic costs such as reduction in agricultural productivity and quality of life beside long-term damages to cultural sites and infrastructure (Heger and Sarraf, 2018).

The Department of Environment (DOE) and the Air Quality Company of Tehran (AQCC) follow an Air Quality Index (AQI) based on the U.S. Environmental Protection Agency (EPA) AQI which ranges from 0 to 500, including four major pollutants in Tehran: particulate matter, nitrogen dioxide, sulphur dioxide, and ozone (Table 1.). For PM$_{10}$ (24 h average) and Ozone (8-h average) the rules are slightly different, and Tehran AQI is less than USA EPA for PM$_{10}$ and Ozone. In recent years (2015–2018), critical pollutants responsible for the majority of unhealthy days are shifted to the PM$_{2.5}$, PM$_{10}$, O$_3$, NO$_2$ and SO$_2$ from CO, PM$_{10}$ and SO$_2$ in order of priority in Tehran. Based on this index, TM experiences 14 clean days (4%), 243 moderately clean days
(67%), 100 unhealthy days for sensitive groups (27%) and 8 unhealthy days for the general population (2%) during March 2017 to March 2018. Relative to the year before, 19 days (7%) have been added to undesirable polluted days (Tehran Annual Air Quality Report, 2018).

Although different mitigation measures such as traffic restriction laws and establishment of national vehicular emission standards based on Euro standards are suggested and implemented over TM, air pollution condition especially for PM$_{2.5}$, O$_3$ and NO$_2$ concentrations have risen in recent years due to reasons such as (Heger and Sarraf, 2018; Mohammadiha et al., 2018; Shahbazi et al., 2016a; Tehran Annual Air Quality Report, 2018):

a) Increasing rate of vehicle numbers and total vehicle kilometer travelled (VKT) and a decrease in the mean traffic speed.
b) Weaknesses in implementation of Vehicle Catalyst Replacement (VCR).
c) Weaknesses in Elimination of Carburetor-Equipped Vehicles (ECEV).
d) Problems in Diesel Particulate Filter Implementation (PDFI).
e) Increasing people’s travel demand due to weaknesses in urban management.
f) Insufficient success in implementing e-government so far.
g) Significant increase in industrial/households energy consumption (Natural gas, Diesel, Kerosene and Mazut) with lag of sufficient national emission standards and novel technologies.
h) Cheap fuel prices (Gasoline, Diesel, CNG and LPG) because of government subsidies and, consequently high per capita consumptions.

Therefore, definition and evaluation of new mitigating strategies with the least damaging side effects are urgent needs for this mega city. As instance, recently, different green programs such as the green belt project and development of parks and other green spaces are suggested and somewhat carried out in Tehran.

2.1.1. Tehran green space characteristics

Based on the Iran Ministry of Roads & Urban Development studies, considering the regional climate, the conventional and acceptable level per capita urban green space in urban areas of Iran is between 7 and 12 square meters per person (Asgari, 2001) which is less compared to the acceptable index of The United Nations Environment Program (20–25 square meters per person). The results of the survey on the current status of green space in Tehran indicate that the per capita urban green space in Tehran is not appropriate and is lower by 2.9 square meters from world standards. On the other hand, distribution of urban green space does not have an acceptable uniformity in 22 districts of Tehran (Bahrami and Aiyanna, 2012).

The current unbalanced distribution of the predominant plant
species types across TM is illustrated in Fig. 1c. Major vegetative spaces are forest parks follows by urban parks and gardens especially in the northern part of the city.

According to the defined indicators such as habitat conditions, water requirements, resistance to pests, diseases, air pollution and water and soil salinity, strength of the species against wind and storm, annual growth, leaf area index, pollen and allergenic particles emission, suitable species plant are selected for Tehran. While in the northern part of the city naturally climatic compatible species such as Platanus Orientalis are planted, in the center and southern polluted areas,

Table 1

<table>
<thead>
<tr>
<th></th>
<th>0-50 (Good)</th>
<th>51-100 (Moderate)</th>
<th>101-150 (Unhealthy for sensitive groups)</th>
<th>151-200 (Unhealthy)</th>
<th>201-300 (Very unhealthy)</th>
<th>301-400 (hazardous)</th>
<th>401-500 (hazardous)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO₂ (ppm) 1-hour</td>
<td>0.00-0.053</td>
<td>0.054-0.100 (0.100)</td>
<td>0.101-0.360</td>
<td>0.361-0.64</td>
<td>0.65-1.24</td>
<td>1.25-1.64</td>
<td>1.65-2.04</td>
</tr>
<tr>
<td>SO₂ (ppb) 24-hours</td>
<td>0.0-0.034</td>
<td>0.035-0.144 (0.144)</td>
<td>0.145-0.224</td>
<td>0.225-0.304</td>
<td>0.35-0.604</td>
<td>0.605-0.804</td>
<td>0.805-1.004</td>
</tr>
<tr>
<td>CO (ppm) 8-hours</td>
<td>0-4.4</td>
<td>4.5-9.4 (9.4)</td>
<td>9.5-12.4</td>
<td>12.5-15.4</td>
<td>15.5-20.4</td>
<td>20.5-20.4</td>
<td>40.5-50.4</td>
</tr>
<tr>
<td>PM₁₀ (µg/m³) 24-hours</td>
<td>0-54</td>
<td>55-154 (150)</td>
<td>155-254</td>
<td>255-354</td>
<td>355-424</td>
<td>425-504</td>
<td>505-604</td>
</tr>
<tr>
<td>PM₂.₅ (µg/m³) 24-hours</td>
<td>0-15.4</td>
<td>15.5-35 (35)</td>
<td>35.1-65.4</td>
<td>65.5-150.4</td>
<td>150.5-250.4</td>
<td>250.5-350.4</td>
<td>350.5-500.4</td>
</tr>
<tr>
<td>O₃ (ppm) 1-hour²</td>
<td>-</td>
<td>-</td>
<td>0.125-0.164</td>
<td>0.165-0.204</td>
<td>0.205-0.404</td>
<td>0.405-0.504</td>
<td>0.505-0.604</td>
</tr>
<tr>
<td>O₃ (ppm) 8-hours³</td>
<td>0.059</td>
<td>0.060-0.075 (0.70)</td>
<td>0.076-0.095</td>
<td>0.096-0.115</td>
<td>0.116-0.374</td>
<td>0.201- (-)</td>
<td>(-)</td>
</tr>
</tbody>
</table>

Notes:
1. The 8-hours average includes 16 periods, the first interval from 4am to 10:59 pm, and the last interval from 1 pm to 7:59 am of the day before.
2. Ozone AQI is calculated for 8 hours average. In areas with a one hour concentration, the indicator is calculated based on the concentration of both 8 hours and one hour, and the larger number is considered.
3. Indicator values greater than 300 for ozone are determined based on one the hour concentration.
Tehran ambient air quality standards values are given in brackets (2016-2017).

Notes: The 8-hours average includes 16 periods, the first interval from 4am to 10:59 pm, and the last interval from 1 pm to 7:59 am of the day before. Ozone AQI is calculated for 8 hours average. In areas with a one hour concentration, the indicator is calculated based on the concentration of both 8 hours and one hour, and the larger number is considered. Indicator values greater than 300 for ozone are determined based on one hour concentration. Tehran ambient air quality standards values are given in brackets (2016-2017).
pollution resistance plants such as Allanthus Allissina, Albizzia Julibrissin, Celis avstruliss and Mprus Alba are used in urban parks. Other suitable species are Eleagnus angustifolia, Gleditsa triacanthos, Quercus rubra, Robinia pseudoacacia, Platanus acerifolia, Betula verrucosa, Fraxinus excelsior, Salix alba and Ligustrum vulgare with limited water requirements (Bahman poor and Salajeghe, 2012; Vahdati et al., 2006; Zaji et al., 1992).

2.2. Description of the model set up and numerical experiments

2.2.1. Modeling air pollution removal by urban vegetation

According to (Rasmussen et al., 1975), air pollutants are removed from the air by three main processes: wet deposition (e.g., transfer of pollutants by precipitation), chemical reactions which consume pollutants (e.g., atmospheric gas phase reactions), and dry deposition (e.g., transfer of gaseous and particulate pollutants to various surface, such as urban trees). Aerodynamic roughness, pollutant concentration, solar radiation, temperature, turbulence, wind velocity, particle size and vegetation surface characteristics, such as stomatal activity and resistances, and leaf surface area are the main factors which influence dry deposition removal rates by plants (Janhäll, 2015; Sehmel, 1980). Dry deposition scheme in WRF-Chem model is based on the multiple-resistance approach described by Wesely (1989).

The pollutant flux to trees is the product of dry deposition velocity ($V_d$) and hourly pollutant concentration (C), such that: $F (g/m^2/s) = V_d (m/sec) \times C (g/m^3)$.

Deposition velocity in Wesely scheme is calculated as the inverse of the sum of the aerodynamic resistance ($R_a$), quasi-laminar boundary layer resistance ($R_b$) and canopy resistance ($R_c$):

$$V_d = (R_a + R_b + R_c)^{-1}$$ (A1)

Where:

$$R_a = 0.74(x u^*)^{-1} \left[ \ln \left( \frac{z}{z_0} \right) + 4.7 \left( \frac{z}{z_0} - 1 \right) \right]$$ stable conditions (A2-1)

$$R_a = 0.74(x u^*)^{-1} \ln \left( \frac{z}{z_0} \right)$$ neutral conditions (A2-2)

$$R_a = 0.74(x u^*)^{-1} \ln \left( \frac{z}{z_0} \right)$$ unstable conditions (A2-3)

Where:

$$R_b = 2(x u^*)^{-1} \left( \frac{Sc}{Pr} \right)^{2/3}$$ (A3)

$$R_c = \left( \frac{r_{rm} + r_{mn}}{r_{mn}} \right) - 1$$ (A4)

$R_b$ and $R_c$ are controlled by surface roughness length ($z_0$). Standard resistance formulas and hourly weather data such as wind velocity, friction and $u^*$ can be used to estimate $R_b$ and $R_c$. $R_a$ can be set to zero unless for particle diameter above 10 mm (Hinds, 1999; Slinn, 1982). $R_a$ has three components: Stomatal resistance ($r_s$), Mesophyll resistance ($r_m$), and Non stomatal resistance ($r_{na}$). Non stomatal resistance includes uptake by other surfaces, such as leaf cuticles, soil or other ground litters (Bruse, 2007; McArae, 1981; Nowak et al., 2006; Wesely and Hicks, 1999).

Stomatal resistance is defined as (Wesely, 1989):

$$r_s = \frac{1}{r_{rms}} \left[ 1 + \frac{1}{200(G + 0.1)^2} \right] \left( \frac{400}{T_s(40 - T_s)} \right) D_{\text{HDO}} D_x$$ (A5)

During the day, the plant stomatal resistance is low, and it plays a major role in the deposition velocity equation. During the night, due to the closure of the plant stomata and limitation in material transfer through the leaves, the stomatal resistance increases and does not show significant effect on the rate of deposition (Wesely, 1989). For symbols of formulations (A1-A5) see Table 2.

### Table 2

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Pr$</td>
<td>Prandtl number for air</td>
<td>0.72</td>
</tr>
<tr>
<td>$r_{rms}$</td>
<td>Minimum stomatal resistance</td>
<td>$z_0$</td>
</tr>
<tr>
<td>$k$</td>
<td>Roughness length</td>
<td>$\kappa$</td>
</tr>
<tr>
<td>$G$</td>
<td>Solar radiation</td>
<td>$L$</td>
</tr>
<tr>
<td>$T_s$</td>
<td>Surface air temperature</td>
<td>$u_*$</td>
</tr>
<tr>
<td>$D_{\text{HDO}}$</td>
<td>Molecular diffusivities for water vapor and for a specific gas $x$</td>
<td>$S_c$</td>
</tr>
</tbody>
</table>

2.2.2. Model configuration

The WRF-Chem system is a regional online atmospheric chemistry model which couples chemistry modules with the WRF model to simultaneously simulate meteorological fields, trace gases and particles at the same horizontal and vertical grids and time step which eliminates the additional interpolations (Grell et al., 2005).

Four simulations (Table 4) are conducted by WRF-Chem version 3.8 coupled with single layer urban canopy model (SLUCM) over four domains (Fig. 2a and b).

Single layer UCM approach assumes parameterized infinitely-long street canyons and represents urban three-dimensional geometry of the building in the city. Shadowing, reflections, and trapping of radiation are considered in street canyons. Monin–Obukhov similarity theory is applied to calculate the total sensible heat fluxes from each surface. Canyon drag coefficient, friction velocity and anthropogenic heat are other parameters which are included in this urban physics scheme (Kusaka and Kimura, 2004; Kusaka et al., 2001). More details about major settings (predefined in WRF model via URBPARAM.TBL) are presented in Table 3. In addition, it is possible to use the option of active green roof in this approach via GROPTION = 1 in URBPARAM.TBL settings which is used in this study (Chen et al., 2011; Yang and Wang, 2014; Yang et al., 2015).

Model configuration details are provided in Table 4. The National Centers for Environmental Prediction (NCEP) global forecast system (GFS) reanalysis data on a $1^\circ \times 1^\circ$ grid are used for the atmosphere and soil initial and boundary conditions (ftp://nomads.ncdc.noaa.gov/GFS/). Preprocessor tool named as mozbc is applied to produce chemical boundary condition (BC) for domain 1 and initial conditions (IC) for 4 domains from MOZART (Model for Ozone and Related chemical Tracers) version 4 (Emmons et al., 2010). Data from coarse domains are used for inner domains boundary conditions. Anthropogenic emission inventory is produced by PREP-CHEM-SOURCES preprocessor (Freitas et al., 2011) from RETRO (REAnalysis of TROPospheric chemical composition) global data (Schultz et al., 2007). Tehran updated emission inventory (Shahbazi et al., 2016a, 2016b) is mapped over the global anthropogenic data in the fourth domain and emissions are introduced to the model through two separate times (wrfchemi_00x12z_A_d04) (Fig. 3). Tehran’s emission inventory for 2013 is based on the main sources of pollutants including stationary sources such as industrial areas, households, terminals and mobile resources (road transport). It has been proved that, in recent years, the emission pattern of pollutants has been changed, considerably. While $SO_2$ emissions in the south and west of the city are significant, namely from the power plants and oil refinery, the emissions of VOCs, CO and $NO_2$ in the city center are higher due to high traffic, as well as the domestic and industrial usages in this megacity.

The 2005 version of carbon bond chemical mechanism (CB05) (Sarwar et al., 2008; Yarwood et al., 2005) and the MADE (Modal Aerosol Dynamics Model for Europe) aerosol scheme (Ackermann et al., 1998) are used for simulations. Model of Emissions of Gases and Aerosols from Nature (MEGAN) is used for biochemistry (Section 2.2.3).

Before conducting simulations, some surface parameters are modified using Sentinel-2A satellite images with the high spatial resolution of 10 m × 10 m (Fig. 1b).
Table 3: Single-layer urban canopy model (SLUCM) parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Low Residential</th>
<th>High Residential</th>
<th>Commercial/Industrial</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRC,URB - Fraction (modified)</td>
<td>0.5</td>
<td>0.9 (0.75)</td>
<td>0.95 (0.85)</td>
</tr>
<tr>
<td>Roof level (building height) [m]</td>
<td>5.0</td>
<td>7.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Anthropogenic heat [W m^{-2}]</td>
<td>20.0</td>
<td>50.0</td>
<td>90.0</td>
</tr>
<tr>
<td>Anthropogenic latent heat [W m^{-2}]</td>
<td>20.0</td>
<td>25.0</td>
<td>40.0</td>
</tr>
<tr>
<td>Surface albedo of roof (modified)</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>IRI SCHEME = 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DZGR [4 layers]: 0.05, 0.05, 0.05, 0.05 [m]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GROFFN = 1 (for GS2 and GS3)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DZGR: 1)Top Soil layer(0.05) 2)Soil layer (0.10) 3) Growing Medium layer (0.15) 4) concrete roof (0.20)[m]</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- F a Fraction of the urban landscape which does not have natural vegetation.
- b Urban irrigation scheme, for vegetation in urban area and green roof.
- c Thickness of each roof layer.
- d Green roof option.
- e Thickness of each layer on green roof.

Table 4: Model configuration and Experiments.

<table>
<thead>
<tr>
<th>Period</th>
<th>2016-06-15,00:00 to 2016-06-28,00:00 (14 days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microphysics</td>
<td>Morrison 2-moment scheme (Morrison et al., 2009)</td>
</tr>
<tr>
<td>Radiation</td>
<td>Long Wave: RRTM (Mlawer et al., 1997)</td>
</tr>
<tr>
<td>Planetary Boundary Layer</td>
<td>Yonsei University scheme</td>
</tr>
<tr>
<td>Land Surface Model</td>
<td>Noah Land Surface Model (Chen and Dudhia, 2001)</td>
</tr>
<tr>
<td>Surface Layer</td>
<td>MMS similarity (Grell et al., 1994)</td>
</tr>
<tr>
<td>Urban Physics</td>
<td>Single-Layer Urban Canopy Model (SLUCM)</td>
</tr>
<tr>
<td>Cumulus Parameterization</td>
<td>Kain-Fritsch scheme only for domain 1 (Kain, 2004)</td>
</tr>
<tr>
<td>Chemistry &amp; Aerosol</td>
<td>CB05 Chemistry with MADE sectional aerosols</td>
</tr>
<tr>
<td>Biochemistry</td>
<td>MEGAN</td>
</tr>
<tr>
<td>Photolysis</td>
<td>Madronich F-TUV (Madronich, 1987)</td>
</tr>
<tr>
<td>Dry deposition</td>
<td>Wesley</td>
</tr>
<tr>
<td>Horizontal spacing</td>
<td>d01: 36 km (47 x 26), d02: 12 km (76 x 28)</td>
</tr>
<tr>
<td>Vertical spacing</td>
<td>d03: 4 km (76 x 43), d04: 1.3 km (103 x 79)</td>
</tr>
<tr>
<td>Time Step</td>
<td>40 full Eta Levels/Model top level: 50hPa</td>
</tr>
<tr>
<td>BC &amp; IC (meteorology)</td>
<td>Global Forecast System (GFS)</td>
</tr>
<tr>
<td>BC &amp; IC (chem)</td>
<td>MOZART</td>
</tr>
<tr>
<td>Observation Data</td>
<td>Iran Meteorological Organization &amp; Tehran Air Quality Control Company</td>
</tr>
</tbody>
</table>

Model Experiments

- Control (C): Modified land use database for the 4th domain
- Green Scenario 1 (GS1): Increase of vegetation fraction by 20 percent
- Green Scenario 2 (GS2): Development of extensive green roof by 30 percent
- Green Scenario 3 (GS3): Multiple Scenario (GS1 + GS2)

Vegetation Fraction for each grid is extracted from NDVI method (Handbook):

NDVI sentinel-2A = (NIR - Red) / (NIR + Red) = (Band8 - Band4) / (Band8 + Band4)

Urban and suburban expansion, as well as Urban Fraction data, also extracted using super classification method by ArcMap10.3 (Fig. 4a). Modified data are mapped to the fourth domain relative variables to represent a more accurate and especially realistic surface characteristic to the model. Indeed, considering the mosaic approach in the WRF model, extraction of land-use fraction is in favor of the correctness of the final numerical results. WRF predefined dataset is compared with the final modified Landuse/Landcover (LULC) used for simulations in Fig. 4b. It must be remarked that for three outer domains, 24 classes USGS (United States Geological Survey) land cover dataset (Wang et al., 2014) was used in all simulations.

The first experiment (Control case) is representative of the existing situation of TM, and its simulated values are selected for conducting the comparative analyses of green scenarios simulations findings. During this simulation, modified LULC data is used for the 4th domain with non-local Yonsei University (YSU) boundary layer scheme (Hong et al., 2006). Three other simulations named as GS1, GS2 and GS3 (Section 2.3) were done for re-simulations of meteorological and chemical variables under the greener urban scenarios.

Two weeks early summer days (15-28 June 2016) with the cloudless condition, calm wind and without precipitation are selected for the simulations. All simulations are initiated at 00:00 UTC June 15 and ended at 00:00 UTC June 28. Primarily plant species of the region are deciduous trees and higher LAI values in early summer is desirable for the purpose of the research. In addition, since green scenarios are long-term and cost-effective mitigating approaches which cannot be easily replaced or omitted from built-up environments, we try to understand their regular behaviors, so a special polluted episode is not selected. Data for the first four days, which is the model spin-up time, is not included in our analyses.

2.2.3. MEGAN vegetation characteristics

Model of Emissions of Gases and Aerosols from Nature (MEGAN) version 2.04 is used for biochemistry input data in this study. In this model vegetation types are classified as four categories: broadleaf trees, needle-leaf trees, shrubs/brushes and herbaceous/crops/pastures. Vegetation data are extracted from remote sensing method with different resolutions (Guenther et al., 2006). Fig. 5 displays isoprene emission factor of MEGAN output for the 4th domain, June 2016. Predominant vegetation types are simulated as grassland and shrub lands (not shown), while as it was explained in section 2.1.1, TM dominant vegetation types are mixed broadleaf and needle-leaf trees, and mixed grasses, shrubs and herbs in the southern boundary of the city, and MEGAN does not correctly capture vegetation type distribution over TM. This issue negatively affects simulation of isoprene distribution. Therefore, vegetation fractions in MEGAN bio-chemical output files are modified before simulations. For this purpose, relative WRF model USGS data are extracted and replaced. We acknowledge the shortcoming of this approach, but due to lack of detailed land cover data in the city scale, it helps to define a more accurate distribution of green space fractions and adjust WRF-Chem and MEGAN land cover data. In the case of GS1 and GS3, additional 20 percent surface vegetation is considered as mixed needle-leaf forests and broadleaf forests, and their fractions are added by 10% in each urban grids.

2.3. Green space development scenarios

Green development scenarios should be rational, realistic and applicable with optimum functionality in the local scale. In this study, three different scenarios are defined and implemented over TM and...
final simulated results are compared to the control current situation case of TM:

- Although the positive effects of surface vegetation like trees in parks, gardens and roadsides on dry deposition of air pollutants are widely proved in previous literature, considering the limited available spaces in the High-Intensity urban areas, it is not practical to develop urban surface parks and trees by more than 20 percent. As a result, in the first green scenario (GS1), surface green vegetative fraction is enhanced by 20 percent with a uniform distribution across each urban grid. USGS predefined data in WRF model consists of 24 land-use/land-cover categories including different vegetation types. Additional UGSs to the urban area is assumed as Mixed Forest land-use category in order to cover all TM tree species described in section 2.1.1. According to the WRF model VEGPARM.TBL table, the characteristics of this class of surface coverage from USGS data are as follows: albedo between 0.17 and 0.25, the height between 10 and 18 m, the emissivity between 0.93 and 0.97, and the leaf area index (LAI) between 2.8 and 5.50.
- Planting vegetation on the building roof is named as Green Roof or Living Roof (Vijayaraghavan, 2016). This green approach solves the lack of space problem in urban areas and has considerable benefits

![Fig. 3. Comparison of Global RETRO Emission Inventories of NO$_2$ and SO$_2$ (Left column) with Local Emission Inventories over the 4th domain (00:00 UTC ~ 03:30 a.m. Local Time & 12:00 UTC ~ 15:30 p.m. Local Time).](image)

![Fig. 4a. Extraction of Landuse/Landcover data from Sentinel-2A images (As an example).](image)
over the city areas such as mitigation of the urban heat island effect due to the higher albedo in the roof level, runoff reduction due to saving water by growth medium, abatement of air pollutants and saving building energy (Shafiquea et al., 2018). Green roofs, according to their weight, maintenance costs and vegetation species are classified into three major kinds: extensive, intensive and semi-intensive (Besir and Cuce, 2018). Development of extensive green roofs is a more cost-effective and economically attractive approach. This green structures need fewer costs of construction and maintenance than intensive green roofs (Ekaterini and Dimitris, 1998). Since applied vegetation types are Moss, Sedum, Herbs and Grasses with limited water needs, for cities such as TM also which suffers from the shortage of water storages, extensive green roofs are more suitable for public usages. Therefore, development of extensive green roof for urban grids by 30 percent is the second defined scenario (GS2). In WRF-UCM predefined UBPARAM.TBL, green roof has a four-layer structure with total predefined depth of 50 cm including a 15 cm soil layer for vegetation (5 cm top soil layer + 10 cm soil layer), 15 cm growing medium layer, and 20 cm concrete roof layer that is considered as extensive green roof and used in this study (Yang et al., 2015). It should be mentioned that although there is no limitation in adding green roof by more than 30 percent, it alters urban morphology by changing predominant land-use category in some urban grids which is not desirable for the purpose of the current study.

- The third scenario (GS3 = GS1 + GS2) is defined as the multiple scenario (increase of surface vegetation fraction by 20 percent + 30 percent development of green roof) in order to see the possible interactive effects between two mentioned scenarios.

3. Model validation

Performance of coupled WRF/Chem/SLUCM model is evaluated for control run at three synoptic weather stations (Geophysics (SW1), Mehrabad Airport (SW2) and Aghdasieh (SW3)) and 10 air quality control stations (AQ1 (Aghdasie), AQ2 (Pirouzi), AQ3 (Tarbiat Modares), AQ4 (Mahalati), AQ5 (Setad Bohran), AQ6 (Zone4), AQ7 (Zone11), AQ8 (Zone16), AQ9 (Shad Abad), AQ10 (Masoudie)) in Tehran (Fig. 2c). Short-term hourly and long-term monthly observational data for major pollutants (CO, O3, NO2, SO2, PM10 and PM2.5) are available at: http://air.tehran.ir for 21 stations over TM.

In this study, the hourly simulation results are extracted and compared to hourly observations from the nearest grid points for meteorological and chemical variables using mean bias error (MBE), mean absolute error (MAE), the root mean square error (RMSE) and Pearson correlation coefficient (R).

The analysis of meteorological variables shows an averaged underestimation of 2m temperature (MBE = −1.68 °C). On the other hand, model over-predicts RH2m (MBE = 1.15%) and 10 m wind speed (MBE = 1.70 m/s). Averaged Pearson correlation coefficients in three selected stations are 0.87, 0.79 and 0.36 for T2m, RH2m and 10 m wind speed, respectively. These findings demonstrate that the applied configuration setting is able to simulate meteorological variables with acceptable accuracies (Fig. 6a.).

The O3 concentration is underestimated by the model and the...
diurnal average (for nine air quality stations) MBE, MAE and RMSE of O₃ are around −6.21, 9.24 and 15.28 ppb, respectively. However, in some station such as AQ3, AQ4, AQ5 and AQ7, model overestimates the O₃ mixing ratios in the midday. Relative values for NO₂ concentrations are −18.45, 19.61 and 27.35 ppb. Model also tends to underestimate SO₂ concentrations in all selected stations except zone11 (diurnal averaged MBE = −2.61 ppb). Computed averaged Pearson correlation coefficients in three selected stations are 0.69, 0.60 and 0.32 for O₃, NO₂ and SO₂, respectively (Fig. 6b).

Acceptable R results revealed that the model accurately predicts chemical variables diurnal trends, while relatively high errors clarify that WRF-Chem model performance has deficiencies in producing gaseous concentrations in TM area. Uncertainties in MEGAN output (The last updated database back to 2002), vegetation distribution (single trees and vegetation species are not correctly introduced to the numerical model; in this case higher resolution satellite images are needed. For example, expensive high resolution images of Quick Bird or Worldview) and TM anthropogenic emission inventory data (The last updated version backs to 2013) cause these errors, especially noticeable quantities for NO₂ which directly influences O₃ prediction, as well. Underestimation of ozone mixing ratio can also be related to the underestimation of NOₓ and VOCs emissions. Some parts of the observed NO₂ and SO₂ errors are due to relatively less-proper background data in TM emission inventory (Fig. 3) which causes less pollutants transfer over the city. Especially in the city center, the errors are due to uncertainty in applied local emission inventory and its speciation. Deficiencies in simulation of PBL height related to the selected boundary layer scheme which is proved in many previous researches like (Banks and Baldasano, 2016; Cuchiara et al., 2014; Parra, 2017; Pérez et al., 2006), as well as the chemical reaction mechanism (mentioned in section 4.1) and the parameterization of dry deposition are another important sources of errors. The function of the dry deposition schemes in numerical models throughout the day with the lack of complexity over flat terrains is relatively acceptable. However, the most important factor in the high uncertainty of the results in the numerical simulations are related to the low accuracy of land use information, especially plant species and soil moisture stress (Wesely and Hicks, 2000). Furthermore, WRF-Chem model shows deficiencies over complex terrain areas (Gurnwani and Mohan, 2017; Ritter et al., 2013). Tehran topographic height is not uniform due to high mountains range in the north and the desert areas in the south which can be the reason for some part of the errors. Full description of the possible sources of ozone simulation errors in numerical simulations by WRF-Chem are available in (Im et al., 2015). Their results indicate that errors in simulation of air temperature, heat fluxes and radiation properties which are related to the microphysics schemes in the numerical models, directly influence O₃ production processes.

It is emphasized here that the accurate performance of the numerical model in simulating the general temporal patterns of air pollutants variations over the study area is also clarified in this section (Fig. 6b - left panels). Thanks to the usage of the TM updated emission inventory in the chemistry part before the main simulations, numerical model is well behaved in capturing the time series of three pollutants mixing ratios over TM, although there are deflections in simulation of the minimum and maximum values, as discussed before.

4. Results

4.1. Diurnal pattern of pollutants surface concentrations

Before the main discussion about the changes in near-surface pollutants concentration after adding new green spaces, it is necessary to have a look at the simulated diurnal patterns of pollutants spatial distributions and local wind field in the control case as a representative of the current situation of Tehran (Fig. 7). Four times are selected for presentations of the pollutants concentrations: midnight (00:00 UTC ~ 03:00 Local Time), morning (06:00 UTC (~09:30 Local Time), afternoon (12:00 UTC ~15:30 Local Time), and evening (18:00 UTC (~21:30 Local Time) hours.

The dominant wind direction during the day is mainly southeasterly which plays an important role in the transfer of pollutants from the industrial areas of the south of the city, especially oil refinery site, to the metropolitan area of Tehran. Transport of SO₂ and NOₓ pollutants to the western border of the city and the city center is evident at 06:00 UTC. In addition, surface ozone mixing ratios are reached to more than 45 ppbv in the presence of solar radiation and high levels of surface NOₓ components due to transferred industrial pollutants as well as heavy morning traffic emissions in the central part of the city. Nitrogen oxides are mainly emitted from natural gas consuming vehicles that have increased in recent years in TM. Daytime PBL growth due to convection processes results in the transfer and vertical mixing of surface contaminants to higher levels above the ground. This reduces the concentration of surface pollutants, and hence, lower levels of surface pollutants are simulated at 12:00 UTC, in agreement with observations. At 18:00 UTC, winds are predominantly from west over the city and from southwest in the south of the city. High levels of pollutants at this time in the city center are clear in simulations results. It should be noted that in the case of ozone, especially in hot summer days, level of ozone

Fig. 6a. Comparison of averaged simulated meteorological variables with observation data using MBE, MBA, RMSE, and R for the Control Simulation in three synoptic weather stations (Geophysics, Mehrabad Airport and Aghdasieh) in Tehran.
production is high in the sub-urban areas and the advection process plays a substantial role on O₃ concentration distribution over the city, which is also clear in Fig. 7, especially, from the northern mountainous areas, or residual layer (above the night time boundary layer that is the remaining of the previous daytime mixed layer) in the night (at 00:00 UTC and 18:00 UTC) and from the eastern desert areas in the daytime (at 06:00 UTC and 12:00 UTC) (Soltanzadeh et al., 2011).

At 00:00 UTC, although the transfer of industrial pollutants to the city is reduced due to the changes in the wind direction, pollutants concentrations in the city center and high residential neighborhoods areas are significant. The nocturnal shallow depth stable boundary layer and the lower wind speed in the city’s canopy layer cause the accumulation of pollutants in this part of the city which are related to the evening time high traffic. The dominant wind pattern is north-westerly, but in the center of the city a noticeable change in the wind has caused atmospheric pollutants to be blocked in this area. Also, the urban plume from industrial sites towards southeast is evident.

At night, the process of ozone production is stopped, and the destruction of surface ozone reduces the concentration of this pollutant in the presence of nitrogen compounds (NOₓ) due to local emissions (titration). However, the shallow depth of the PBL and its static stability and hence, lower turbulence; and transfer of ozone from the upper layer by topographic driven katabolic winds (residual layer) can slightly increase the surface concentration of this pollutant in some areas, especially in the northern areas of the city. The CB05 chemical mechanism generally tends to under predict diurnal ozone concentration due to rapid rate of NOₓ to HNO₃ conversion processes and underestimation of NO₂ (Henderson et al., 2011). Nighttime simulated values are reached about 30 (20) ppbv over the city at 06:00 UTC (00:00 UTC) with about 10 ppbv overestimation in comparison to observations which is attributed to a higher vertical mixing coefficient in the model (Castellanos et al., 2011) and errors in boundary layer height simulation.

Results also show an increase in ozone concentrations with altitude in the city (higher values in the north of the city), which is also consistent with previous findings (Ritter et al., 2013).

The overall diurnal observed patterns demonstrate the importance...
of the atmospheric dispersion process and changes in the dominant local wind direction. Also, the usage of local anthropogenic emission inventories in the more realistic and reliable simulations of near-surface pollutants spatial-temporal distributions in the city-scale research like the current one is proved.

In the next section, variations of pollutants mixing ratios after conduction of green scenarios are analyzed in detail. For better understanding of the interaction between meteorological and chemical variables, simulated alterations in near surface air temperature, near surface local wind speed and PBL height are firstly discussed in a separate section.

4.2. Variations in meteorological and chemical variables

4.2.1. Meteorology

3 days averaged (19-06-2016 to 22-06-2016) differences in 2 m temperature (T2m), 10 m wind speed and planetary boundary layer height (PBLH) values after implementations of defined green scenarios over TM (Section 2.4.) are illustrated in Fig. 5a. Two selected times 00:00 UTC (local time ~ 03:30 a.m.) and 06:00 UTC (local time ~ 09:30 a.m.) are chosen for the analysis.

Fig. 7. O₃ (first column), NO₂ (second column) and SO₂ (third column) concentrations at 00:00 UTC (~03:30 Am Local Time), 06:00 UTC (~09:30 a.m. Local Time), 12:00 UTC (~15:30 p.m. Local Time) and 18:00 UTC (~21:30 p.m. Local Time) over the 4th domain.
p.m.) as representative of the nightly stable and daily convective conditions, respectively, are illustrated and compared.

4.2.1.1. Near-surface air temperature. $T_{2m}$ depends on surface properties, such as surface albedo and heat capacity which are directly influenced by land-use properties. Adding vegetation to the urban area changes land use and its related variables which cause clear variations in daily $T_{2m}$. Enhanced nighttime 2 m air temperature values are obvious through all simulations but with different values. GS2 shows the strongest warming effect (up to 2 °C) in comparison to GS1 and GS3 simulations. Nocturnal observed warming effects in the first and third scenarios are the result of the lower sky view factor over the city canyons with more trees which traps more outgoing longwave radiation and anthropogenic heat released in the crowded area of the city (Qiao et al., 2013).

On the other hand, addition of surface trees to the urban canopy causes a reduction in incoming daytime solar shortwave radiation because of shading and higher albedo of green leaves relative to urban structures. Enhanced evapotranspiration in the presence of plant photosynthesis process also results in the reduction of ambient air temperature. Cooling daily impact is observed up to −1 °C across the city in the case of GS3, more intense values in comparison to GS1 (−0.6 °C) and GS2 (−0.8 °C).

In the case of green roof, more (less) warming (cooling) effect during the night (day) is observed which is consistent with previous studies. For example (Solcerova et al., 2017), in their research observed net diurnal warming effects of extensive green roofs. They show that cooling performance of green roof is related to the irrigation and vegetation type, and at night, especially in summer dry condition, cooling performance of these green infrastructures is not meaningful. Wind speed reduction, especially at night, also may cause less natural heat ventilation over the city, causing enhanced 2 m air temperature.

4.2.1.2. 10m wind speed. Wide areas of the leaves increase the aerodynamic resistance and therefore reduces the wind speed (Bealey et al., 2007). Modification of the surface roughness in urban areas also causes changes in the local near surface wind speed and wind direction (Vahmani et al., 2016). Trees are acting like blocks enhancing surface roughness, so it is not surprising that 10 m wind speeds are lower for the greener surface simulations. Except for nighttime positive values which are observed in the north region of the city (may be due to katabatic winds), the total diurnal trend decreases. Detracted values reach to −0.9 ms$^{-1}$ in the city center in all scenarios. Daily values are more intense and reach to more than −1.5 ms$^{-1}$ in GS1 and GS2.

Fig. 8a. Actual and differences (scenario-control) of meteorological variables (2 m Temperature, 10 m wind speed, PBLH) caused by conducting defined green scenarios (GS1, GS2 and GS3) in comparison to the control simulation (the left column) for two times: 00:00 UTC (~03:30 a.m. Local Time as representation of the stable boundary layer) and 06:00 UTC (~09:30 a.m. Local Time as representation of the convective boundary layer). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Observed relatively higher reduction in the green roof scenario due to the increase of the friction (roughness) of the roof surface is rational, because according to predefined values in WRF model urban setup, average building height is 10 m for the high residential urban category.

4.2.1.3. Planetary boundary layer height (PBLH). PBLH is an important parameter that directly influences the air pollutant dilution and mass transport. Daily averaged quantities of PBLH show an average reduction up to ~200 m in the city center in the case of GS1 and GS2, and up to ~300 m in the last scenario. Maximum observed values are simulated in the city center in three developmental green scenarios.

Alteration in this variable is positive for the night. More variations are observed in the city center in GS1 and GS3 up to 100 m. In green roof scenario, with warming effect, PBLH reaches more than 200 m in the northern part of the city which clearly follows the increasing pattern of air temperature.

Lower mean temperature and less net surface solar radiation cause less buoyancy and turbulence mixing during the day that result in less PBLH, while at night, enhanced air temperatures cause higher simulated PBLH. As it is expected, diurnal changes of this variable is clearly conform to the alterations of near-surface air temperature.

4.2.2. Chemistry

4.2.2.1. Mixing ratios. Practically, adding vegetative areas, by reduction of air temperature, may decrease energy consumption and anthropogenic heat and pollution. In this study, this issue is ignored and anthropogenic heat and pollution releases are the same in all simulations (indeed, in all simulations, TM emission inventory and predefined anthropogenic heat in the URBPARAM.TBL settings are the same). Therefore, any observed alteration in pollutants mixing ratios is the result of the changes in boundary layer structure and wind field.

Alterations in gaseous mixing ratios after conducting the three defined scenarios are illustrated in Fig. 8b. Surface ozone concentrations is increased by 8 (10) ppbv at night (day) in GS1. The relative values for GS2 and GS3 are nearly 4 (10) ppbv.

As discussed previously, in the night, the main source of pollutants over TM is anthropogenic pollution in the city center and highly crowded areas. The promotion of surface ozone concentrations during the night in the presence of the ozone depletion process, is the result of the aerodynamic effects of the green coverage added to the city on wind speed (reducing it) which is mentioned in the previous section. This process can reduce ventilation of polluted air, especially in the city center. Furthermore, enhanced boundary layer height, turbulence and instability due to the increased night temperature (Fig. 8a.), improve the NOx upward physical transport and reduces the amount of ozone titration. Although it is anticipated that reduction in the wind speed and the advection transport of sub-urban ozone, reduce the surface level of this pollutant in city center, simulations prove that boundary layer structure is the more effective factor on the O3 mixing ratio. The incremental patterns of simulated variations are the same for three selected scenarios, slight differences are observed in predicted values. The maximum nightly increased values for O3 is simulated in the first scenario (surface vegetation). In the cases of NO2 and SO2, the combination of the surface and roof vegetative areas (GS3) show the most unwanted effects on air quality in the day while the nighttime performance are almost the same. These results prove that for primary pollutants, ground level concentrations mostly depend on air ventilation over the city while in the case of O3 both the air ventilation and NOx emissions are important factors.

Although the general patterns of simulated variations are the same for three selected scenarios, slight differences are observed in predicted values. The maximum nightly increased values for O3 is simulated in the first scenario (surface vegetation). In the cases of NO2 and SO2, the combination of the surface and roof vegetative areas (GS3) show the most unwanted effects on air quality in the day while the nighttime performance are almost the same. These results prove that for primary pollutants, ground level concentrations mostly depend on air ventilation over the city while in the case of O3 both the air ventilation and NOx emissions are important factors.

4.2.2.2. Dry deposition velocity. During the day, an increase of Vd up to 0.01 cm/s is observed in GS1 and GS3 for three pollutants (Fig. 8c). Although less wind speed causes less frictional velocity, the enhanced roughness compensates this effect and decreases the values of Rb and Rf, which caused higher simulated Vd. It should be noted that the reduction of the buoyancy term in the TKE equation reduces the friction velocity during the daytime, which has a decreasing effect on the rate of daily deposition velocity (Stull, 1988). Nevertheless, the incremental trends of this variable in GS1 and GS3 are due to the prevalence of the
expression of stomatal resistance during the day. During the summer, higher air temperatures may cause higher stomatal resistance in plants since they stop evaporation to save water content of the leaves especially when soil is not irrigated (Section 2.2.1.). This factor has deteriorating impacts on the estimation of daytime $V_d$. According to the Iran Meteorological Organization (http://www.irimo.ir), averaged and maximum air temperatures in July 2016 over TM reached 28 °C and 39.2 °C, respectively. Therefore, in this situation, lower temperatures are in favor of the dry deposition process, and lower stomatal resistance results in higher $V_d$.

Related changes in the green roof scenario are decremental, as the extensive green roofs studied in this research, do not make a significant change in surface roughness, and that the wind speed is lowered at the roof level (the default height of the buildings in the urbanized high residential area).

In the absence of plants stomatal biological function at night, predominant terms in $V_d$ equation are $R_a$ and $R_b$ which are directly influenced by wind speed variations. Therefore, as expected, decreased deposition velocities at night, especially in the central parts of the city, are followed by the wind speed reduction pattern (Fig. 8a).

4.2.2.3. Deposition fluxes. The result of the interaction between the changes in land-use properties and meteorological parameters of the urban canopy layer, as well as the changes in the concentration of pollutants in urban green space development scenarios show that due to the increase of surface concentrations of pollutants, daytime deposition fluxes in all regions of the city (except for the western margin) have been enhanced (Fig. 8d). The lowest amounts are related to the NO$_2$ with a maximum increment up to 0.05 $\mu$g/(m$^2$s) in GS1 and GS2. Relative quantities in the last scenario have reached 0.15 $\mu$g/(m$^2$s). SO$_2$ deposition fluxes follow similar spatial trends to that of NO$_2$ but with more intense values up to more than 2.0 $\mu$g/(m$^2$s) in GS3 and 0.5 $\mu$g/(m$^2$s) in GS1 and GS2.

Deposition flux values are estimated to augment by more than 1.5 $\mu$g/(m$^2$s) for ozone in the proposed scenarios. The deduction of this variable in GS1 in the city center (less than 0.2 $\mu$g/(m$^2$s)) corresponds to the wind speed pattern of the region, and the significant reduction in the western region of Tehran in GS1 and GS2 is consistent with the reduction pattern of the pollutant concentrations. In conclusion, we admit that prediction of the general trends of deposition flux variations through selected scenarios over the city is not readily possible.

![Fig. 8c. Same as Fig. 8a but for gaseous pollutants dry deposition velocity.](image)
4.3. The relationship between isoprene emission and O₃ concentration

In Fig. 9, the correlation between alterations in O₃ and isoprene concentrations through GS1 and GS2 simulations (12:00 UTC ~ 15:30 local time) over urban grid points are compared. Calculated Pearson correlation coefficient values are 0.11 in the cases of GS1 (Mixed Forest) and 0.02 in GS2 (Herbaceous plants). Although the discussion on the emission of VOCs by plant species is out of the scope of this study, the proximity of surface green spaces to the sources of NOₓ production can be a reason for this result.

In addition, emission of these compounds depends on solar radiation, air temperature and daily biological function of plants, and reductions in these variables cause reduction in VOCs emission (Cardelino and Chameides, 1990). Therefore, it can be concluded that this green infrastructure has a less undesirable effect on the trend of increasing ozone concentration than GS1.

Detailed analysis of numerical results also shows that emissions of monoterpenes such as α-pinene, β-pinene concentrations in GS1 and GS3 simulations are increased by the order of ~10⁻⁴ ppbv, but results are insignificant (~10⁻⁶ ppbv) for GS2.

4.4. Limitations

The depleted amount of pollutant from the atmosphere due to the dry deposition process is obtained from the following equation (Janhäll, 2015):

\[
\text{Deposition amount (g/m}^2\text{)} = V_d (\text{m/s}) \times C (\text{g/m}^3) \times t \times \text{LAI}
\]

The leaf area index (LAI) is a dimensionless variable that depends on plant species and physical properties of the plant leaf. In order to accurately estimate the amounts of removed pollutants, accurate high-resolution information of the distributions of urban vegetation cover and plants species in different parts of the city is required. For example, the UFORE model is one of the urban green space management tools that uses meteorological and chemical data as well as vegetation information such as plant type, age, height, and leaf area index in order to estimate the atmospheric pollutant removal rates, as well as emission rates of volatile organic compounds with relatively acceptable accuracy (Nowak and Crane, 2000).

In addition, in the Wesely deposition scheme, which is pre-assumed to be used in the WRF-Chem model, the leaf area index is not included, which is one of the most important shortcomings of this numerical scheme (Wesely, 1989). The study of (Val Martin et al., 2014) has shown that correction of the deposition scheme with the direct consideration of the leaf area index in the equation of stomatal resistance (\(R_s\)), significantly improved the model performance in estimating the O₃ deposition and concentration of ozone, particularly in areas with dense vegetation. Uncertainty in minimum summertime stomatal resistance (\(r_{\text{min}}\)) in this scheme is another source of error for concentration calculations.

Given the limited access to the LAI and vegetation species information in this study, authors are satisfied by the numerical estimation of the deposition fluxes of pollutants using simulation results, and findings have been reported from the approach of studying the aerodynamic effects of urban green spaces on deposition speeds and boundary layer variables, as well as the importance of the release of volatile organic compounds on surface ozone concentrations.

It should be mentioned that due to the lack of observational data, model performance in simulating deposition velocity is not validated...
which may negatively affects our assessments. More researches are also needed to assess variations in PM10 and PM2.5 concentrations and their effects on solar incoming and long wave outgoing radiations due to alterations in reflecting and scattering properties of the near surface radiation, that are directly related to ozone production.

Further studies are also needed to investigate and compare the effectiveness of the green mitigation strategies for other seasons in Tehran. Pathways to improve the spatial-temporal air pollutants concentration forecasts by the multi-model system, ensemble forecasting and ensemble-based data assimilation are also suggested for Tehran metropolis.

5. Conclusion

The advanced Weather Research and Forecasting & Chemistry (WRF-Chem version 3.8) coupled with SLUCM modeling system is employed to numerically investigate the effects of adding diverse vegetative areas on air quality and abatement of three gaseous air pollutants over Tehran Metropolis, for the first time. Three executable green surface scenarios are designed and conducted (Adding surface trees by 20%; Development of green roof by 30%; Multiple scenario: Adding surface trees by 20% & Development of green roof by 30%) and results are compared to control case as the representative of current distribution of green spaces over the city.

Main results of the current research are summarized as:

1. Structure and dynamic of the PBL strongly control the concentration of near surface pollutants over TM. This result is in line with previous findings such as (Parra, 2017; Pérez et al., 2006). Although suggested green scenarios are beneficial for improving air quality via reduction in the air temperature which is expected to slow down the rate of chemical reactions and cause reduction in energy consumption, they may not be reliable solutions for the serious air pollution environmental issues in TM. Implementations of green scenarios alter the heat budget of the near surface atmosphere, PBL depths and especially wind speed that drive changes in the dispersion pattern and horizontal and vertical transfer of pollutants. As a consequence, adding green areas affect near surface pollutants concentrations. In spite of the positive effect of wind speed reduction on transferring industrial polluted air over the city, reduction in heat and pollution natural ventilation (as a combined effect of dispersion and vertical mixing) is a negative side effect of green scenarios in Tehran which suffers from diurnal low level of wind speed. Case studies like this prove that the any change in the urban structure and land-cover properties influence the local meteorological conditions and the boundary layer structure, thermodynamically, that are responsible for the deterioration of air pollution in megacities.

2. Considering both positive and negative environmental effects of green scenarios on Tehran air quality, comparison between surface and roof level green scenarios proves that suggestion of the more beneficial approach is not convincing.

3. According to the Atmospheric Transport Model Evaluation Study (ATMES), parameterizations of the source terms and deposition processes are the main source of errors in numerical simulation (Klug et al., 1992). Current results also indicate the need to use the updated regional emission inventories in the local air quality studies since diurnal predominant wind direction is responsible for transporting pollutants from emission hotspots, such as industrial regions, over the city, especially in the case of primary pollutants such as SO2, NO2 and NMVOCs.

4. Simulations suggest that alterations in surface dry deposition velocity and deposition flux are mainly controlled by the PBL and surface variables. These are especially sensitive to roughness length and wind speed. These results are in line with previous findings which proved that the aerodynamic effects of trees were more important than deposition (Section1.). Shortcomings in Wesely dry deposition scheme due to not directly taking into account vegetation properties and errors in computing stomatal resistance and canopy resistance (Rc) should be considered in this result.

5. In the case of O3, a slightly meaningful correlation is found between observed enhanced O3 and isoprene mixing ratios over the city which has a non-significant negative influence on air quality. Green roof approach showed less unwanted impacts. However, considering the calculated Pearson numbers, this factor is less important in comparison to the PBL variables influences.

6. Finally, we should admit that adoption of urban greening programs for megacities with high level of air pollution is not a straightforward process. Factors as the great expansion of Tehran metropolis, the complex topography and climate of the region, the complex urban morphology, industrial pollution sources in the western and southern margins of the city and significant traffic in the central and commercial areas of the city, all cause non-uniformed alterations in patterns of meteorological and air chemistry variables across the city in three suggested scenarios. Therefore, before implementing the green space development plans that are designed to moderate the heat island and improve the air quality of metropolitan areas, the adverse and negative side effects of these green structures in different areas should also be considered. This research is the first step in evaluating green scenarios effects on air quality in Tehran Metropolis, using on-line coupled meteorological-chemical numerical model, as well as a new remote-sensing approach for definition of land-use and land-cover properties to the numerical model by free available satellite images. Especially, the corrections of urban fractions can let us to add additional surface vegetation to the city. Authors also suggest similar local scale studies to evaluate the ongoing green programs like the Green Belt Project of Tehran.

Acknowledgments

Let us acknowledge the Iran Meteorological Organization (IRIMO), the Iran’s Department of Environment (DOE) and the Air Quality Control Company of Tehran Municipality (AQCC) for providing essential observational data. We acknowledge use of NCAR/ACOM MOZART-4 global model output available at http://www.acom.ucar.edu/wrf-chem/mozart.shtml. Funding is provided by University of Hormozgan (Bandar Abbas, Iran).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2019.116832.

References


Wesely, M.L., Hicks, B.B., 1977. Some factors that affect the deposition rates of sulfur dioxide and similar gases on vegetation. J. Air Pollut. Control Assoc. 27, 1110–1116.


