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Inter-annual variations and trends of the urban warming in Tehran

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ABSTRACT

Urbanization is an extreme case of land-use change which amplifies in most cases the regional warming, and highly impacts a number of sensitive sectors, particularly human health. Using near-surface daily temperature records for a 63-yr period from 1951 to 2013, temperature changes over the urban city of Tehran were examined. Statistically significant warming trend of the order 0.37 °C/decade has been observed, leading to 2.3 °C rise over the entire 63-yr period, and the warming trend has been intensified in recent years. The observed warming in the urban city of Tehran has been more than triple the rate of change in the global average temperature, indicating that urbanization has had a significant warming effect. The nighttime warming (0.62 °C/decade) in the urban city of Tehran was found to be more than three times greater than the daytime warming (0.17 °C/decade), resulted in a decreasing trend in the diurnal temperature range (DTR; i.e. the difference between the daytime maximum and nighttime minimum temperatures). In a similar manner, a decreasing trend in the number of cold nights was identified, and the rate was more than twice as high as the rate of increase in the number of warm days. From a seasonal perspective, warming trends of the urban city of Tehran have been found to be nearly identical in winter and summer, with the rates of 0.35 °C/decade and 0.33 °C/decade, respectively. However, a seasonal cycle in the changes of the DTR was identified, with a stronger decrease rate in winter than summer because while the nighttime warming (which has been greater than the daytime warming) has not changed considerably from winter to summer, the daytime warming has been stronger in summer.

1. Introduction

Over recent years, the climate of urban areas has changed rapidly as they are exposed to the greenhouse warming and urban heat island effects. Although it is well established that changes in the concentration of greenhouse gases (GHGs) owing to human activity have contributed to the warming effect (Ahuja and Lashof, 1990), a major portion of the temperature increase in some locations during last decades has been caused by urbanization and other land-use changes (Kalnay and Cai, 2003; Stone, 2007; Fujibe, 2009; Founda, 2011; Founda et al., 2015). Indeed, previous studies have shown a clear division in temperature trends between large cities and neighboring rural areas (e.g. Stone, 2007; McCarthy et al., 2010; Ren and Zhou, 2014; Zhang et al., 2014). This underlines the need to quantify the degree to which background temperature trends are amplified by urbanization.

Since the early investigation by Howard (1833), a great deal of attention has been given to the urban heat island effects, using both experimental and modeling approaches (e.g. Kalnay and Cai, 2003; McCarthy et al., 2010; Argüeso et al., 2014). By comparing surface temperature observations with the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis data (which did not consider changes to the land surface) for the period 1950–2000, Kalnay and Cai (2003) estimated a warming trend of the order 0.027 °C/decade in the continental United States due to land-use changes. A decrease in the diurnal temperature range (DTR, i.e. the difference between the daytime maximum and nighttime minimum temperatures) was also identified, half of which was attributed to the urban effects and other land-use changes. Later, Kalnay et al. (2006) rectified some of the shortcomings in the approach of Kalnay and Cai (2003) and estimated that land-use changes resulted in an increase of the mean air temperature of the continental United States by the rate of 0.09 °C/decade, while the DTR has been decreased by the rate of −0.05 °C/decade. Similarly, observational analyses by Stone (2007) indicated a warming trend of the order 0.05 °C/decade due to the urban heat island effects over the continental United States for the period 1951–2000. By comparing homogenized station datasets with gridded temperature products and using sea surface temperature (SST) datasets, Jones et al. (2008) attempted to assess possible urban influences over the east of the Chinese mainland. They estimated an urbanization warming rate of 0.1 °C/decade for the period 1951–2004, although they argued that the urbanization warming has been much less than the overall climate warming of this region, which was estimated to be 0.81 °C/decade for the same period. The identified urbanization warming by Jones et al. (2008) is close to the estimate made by Ren

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et al. (2008) over north China for the period 1961–2000 using 282 meteorological stations, classified as rural, small city, medium city, large city and metropolis. Their results indicated higher urban warming in large (0.16 °C/decade) compared to small (0.07 °C/decade) cities of north China.

Some studies have even reported substantially higher urbanization warming trends in densely populated areas. For example, a warming trend of the order 0.31 °C/decade was observed over the urban city of Tokyo for the period 1906–2000, which is substantially higher than the warming trend of 0.06 °C/decade at Hachijo Island, 300 km south of Tokyo for the same period (Fujibe, 2009). The significant urban warming identified in these studies underlines the need for inclusion of currently missing impacts of urbanization in climate models (Christensen, 2007).

While contribution of urbanization to the temperature increase at local and regional scales has been widely accepted, a stronger rate of increase in the minimum temperature compared to the maximum in urban areas has been identified (e.g. Karl et al., 1984; Karl et al., 1993; McCarthy et al., 2010; Argüeso et al., 2014; Founda et al., 2015). The increase of the minimum temperature at a faster rate than the maximum, and a subsequent decrease in the DTR was first identified by Karl et al. (1984). Later, by analyzing maximum and minimum temperatures obtained from more than 2000 stations across the global landmass, Karl et al. (1993) found that the rise of the minimum temperature occurred at a rate three times that of the maximum during the period 1951–1990. Using an urban land surface scheme coupled to a Global Climate Model (GCM), McCarthy et al. (2010) investigated climate change in response to both doubling atmospheric carbon dioxide levels and urban land effects. They demonstrated that in some populated areas warming due to urbanization is comparable to the warming associated with doubled CO_2. Their analyses indicated that an increase in the minimum temperature due to urban land effects in regions with a sub-tropical arid climate is comparable to the warming caused by doubled CO_2, while the increase of the maximum temperature is predominantly attributed to the doubled CO_2. More recent numerical analyses by Argüeso et al. (2014)) and an observational investigation by Founda et al. (2015) have also suggested that urbanization more strongly increases the nighttime temperatures. The greater nighttime warming has primarily been attributed to the high heat storage of urban areas, the obstruction of night-time outgoing longwave radiation, anthropogenic heat release and the reduced evapotranspiration in the city environment (e.g. see Kusaka and Kimura, 2004a).

Warming is expected to be profound in Tehran, over which rapid urbanization and an increase in the concentrations of GHGs in its atmosphere have been taking place during the last half century. A significant urbanization warming in the metropolitan urban area of Tehran was highlighted in the numerical analyses by (McCarthy et al., 2010). Their results indicated that the impact of urbanization on the increase of nighttime temperatures is significantly larger in Tehran compared to other megacities of Beijing, Delhi, Lagos, London, Los Angles, Sao Paulo and Sydney. They found that the number of warm nights over the urban city of Tehran has been significantly more than its neighboring rural areas, while, in comparison, the urbanization warming was found much less over the other abovementioned megacities.

Despite rapid urbanization and significant enhancement of GHGs in its atmosphere, few studies have been conducted to investigate Tehran's temperature changes associated with these environmental effects. This paper, therefore, presents observational-based analyses to quantify temperature changes in the urban city of Tehran for a 63-yr period from 1951 to 2013. In addition, through comparison of changes in the minimum and maximum temperatures, we provide an estimate for the mean decadal rate of change in temperature caused by urbanization and the greenhouse warming.

The paper is organized in the following way. Section 2 presents the data description. Section 3 provides a brief overview of the climate of Tehran, while some demographic information are presented in Section 4. Results are discussed in Section 5, which include a long-term trend of the annual mean air temperatures; trends of the maximum and minimum air temperatures; and seasonal variations in the temperature trends in the urban city of Tehran. Discussions are provided in Section 6, while an overall summary and conclusions are presented in Section 7.

2. Data description

Ground-based observed meteorological data with an hourly temporal resolution is available at a synoptic weather station at Tehran Mehrabad airport (35.7 N, 51.3 E and 1190.8 m above mean sea level; Fig. 1) since 1951. Daily mean, maximum and minimum air temperature and accumulated precipitation records at Tehran Mehrabad airport for a 63-yr period from 1951 to 2013 were obtained from the Meteorological Organization of Iran. The obtained observation datasets have been quality controlled by the Meteorological Organization of Iran, which include gross error limit checks, internal and time consistency checks and space/time consistency checks. Daily mean air temperatures were calculated from 3-hourly temperatures, while annual and seasonal anomalies were calculated relative to the corresponding annual and seasonal mean of the entire period of 1951–2013, unless otherwise stated. Mehrabad airport was initially established at a small village west of Tehran in 1938. However, following the rapid expansion of Tehran, the airport is now located in the west heart of the city. Location of the synoptic weather station at the airport has not changed since its establishment. To understand the impacts of the year-to-year climate variability on temperature changes of Tehran, the NAO indices were obtained from the Climate Analysis Section, NCAR, Boulder, United States (Hurrell, 1995). The NAO index is defined as the difference of the atmospheric sea-level pressure between the Icelandic low and the Azores high.

3. Climate of Tehran

Tehran is located in the southern foothills of the Alborz Mountains, the mountain ranges by which the Caspian rain-bearing winds are blocked (Fig. 1). Tehran's climate is largely affected by its geographic location (Crosbie et al., 2014), such that it is wetter and cooler on the hilly north side compared to the flat south part. The climate of Tehran is characterized by hot-dry summers, but cool semi-dry winters during which the Rossby-forced advection of the Mediterranean air masses cause often weak to moderate, but occasionally heavy precipitation events. The observed long-term (1951–2013) summer (June–July-August) and winter (December–January–February) daily mean air temperatures are 29.1 and 5.1 °C, respectively at the Mehrabad airport weather station, which is representative of west central lowlands of Tehran. Tehran has a semi-arid climate, with an annual accumulated precipitation of 233.4 mm and an average annual temperature of 17.4 °C, observed at the Mehrabad airport over the 63-yr period. Observations indicate that precipitation in Tehran is the highest between November and April, and the lowest in the warmest months between June and September. Maximum and minimum monthly accumulated precipitation has been observed in March (39.1 mm), and September (1.1 mm), respectively (Fig. 2).

4. Demographics of Tehran

Population of the city of Tehran has been rapidly increasing over the past half century, reaching from approximately 1.5 million in 1956 to 8.2 millions in 2011 (Asgharpour, 2013; Ghadami et al., 2013). As a consequence, the urban built surface coverage of the city of Tehran has been also growing rapidly, reaching from 100 km^2 in 1956 to approximately 800 km^2 in 2006 (Ghadami et al., 2013). Such rapid expansion of the city has caused significant destruction of the agricultural lands and natural resources (Shahraki et al., 2012). The rapid population growth of Tehran has also led to a significant increase in the number of motor vehicles,

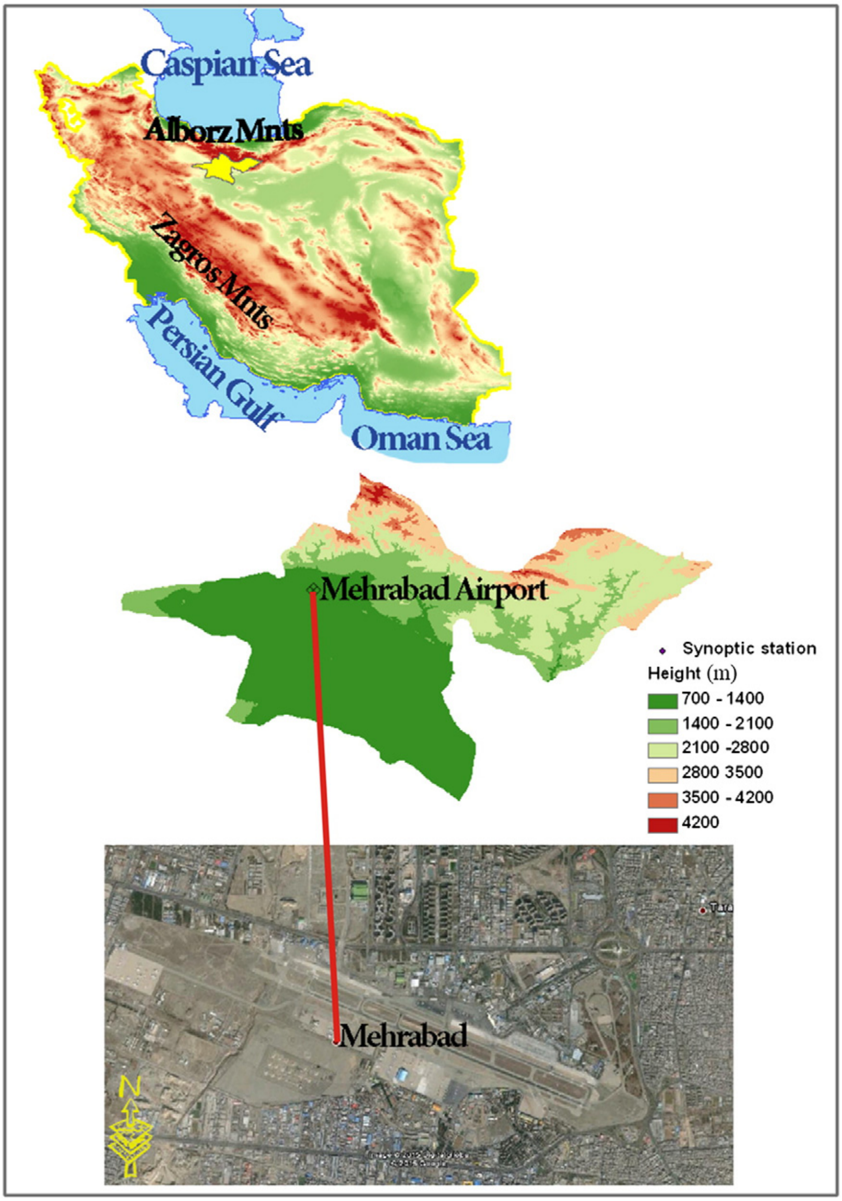

Fig. 1. The location of Tehran metropolitan area (depicted by the yellow color on the top panel and enlarged in the middle panel), along with two major topographic features of Iran: the Alborz mountains in the north and the Zagros Mountains that extends from northwest to south of Iran. The location of a synoptic weather station at the Mehrabad airport is also shown on the bottom panel.

such that the number of private cars for 1000 people has been increased from 5 cars in 1956 to 90 cars in 2006 (Roshan et al., 2010). With this significant expansion and population growth of the urban city of Tehran, it has been estimated that the annual anthropogenic heat release of the city reached to 27 W m $^{-2}$ in 2011 (Stewart and Kennedy, 2015). Changes in population, the urban surface coverage and the number of cars in Tehran in different years are presented in Table 1.

5. Results

5.1. Annual mean temperature trend

Annual mean temperature anomalies along with the linear regression line at Tehran Mehrabad airport and the annual NAO index from 1951 to 2013 are shown in Fig. 3. In spite of the inter-annual variations, Tehran's annual mean air temperature has been increasing between 1951 and 2013, although some comparatively short cooling periods have also occurred. Our analyses indicate a statistically significant warming trend of the order 0.37 °C/decade, such that a temperature increase of 2.3 °C over the entire 63-year period has been observed. Towards the end of the period, between 1983 and 2013, the warming trend has further increased to 0.48 °C/decade, indicating that Tehran has been warming at an increasing rate. The observed warming trend of 0.37 °C/decade during the entire period is more than triple the rate of change in the global average temperature, estimated to be 0.09 and 0.1 °C/decade over the past 50 years (from 1960 to 2010) under the Goddard Institute for Space Studies Surface Temperature Analysis (GISTEMP) and the Hadley Centre and Climate Research Unit (HadCRUT3) datasets, respectively (European Environmental Agency, 2011). More significant warming of the urban city of Tehran compared to the global warming is mostly attributed to the impacts of urbanization, as further discussed in the next subsection. The identified warming trend in the urban city of Tehran is comparable to the observed warming trend of 0.31 °C/decade in the urban city of Tokyo for the period 1906–2000.

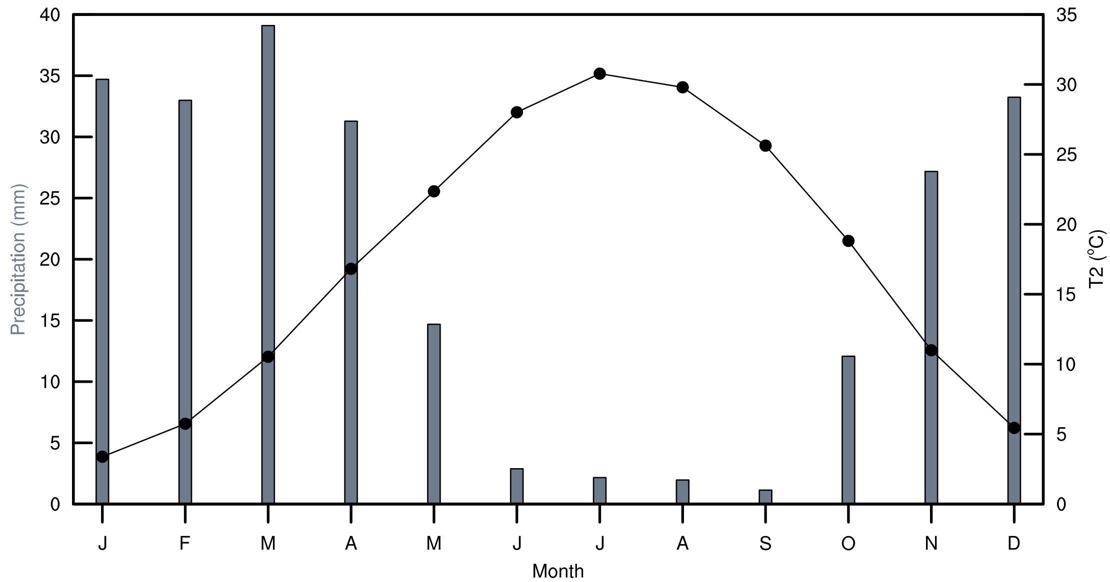

Fig. 2. Monthly mean near-surface air temperatures (°C, black line) and monthly accumulated precipitations (mm, bars) at Tehran Mehrabad airport averaged for the period 1951–2013.

Further analysis of Fig. 3 indicates that temperature anomalies in Tehran have been started to be continuously positive since 1987, with the exception of 3 years of negative anomalies in 1991, 1992 and 1993, possibly due to the eruption of Mt. Pinatubo in the Philippines in June 1991, indicating a fast response of the surface temperature to the increased stratospheric aerosols. Indeed, Table 2 indicates that the last three decades since 1980 have been successively warmer than any preceding decade, and in terms of temperature the last decade stands substantially above any other 10-year periods since 1951. It is interesting to note that over the last 16 years (from 1998 to 2013), the rise of Tehran's near-surface air temperature has been faster than previous decades, in contrast to the global scale, for which a reduced rate of warming has been observed since 1998 (Murphy et al., 2009). Indeed, the last 16 years from 1998 to 2013 were among the warmest years since 1951, and 2010 has been the warmest year, exceeding the 1951–2013 mean air temperature by 2.2 °C. At the other end, Tehran's coldest year during the period 1951–2003 was 1972, with 2.2 °C lower than the 1951–2013 mean air temperature (Fig. 3).

Fig. 4 displays temperature and precipitation anomalies in winter, the season with the highest precipitation in Tehran. Similar to the long-term annual mean air temperatures, statistically significant warming trend is evident in winter. The figure suggests that warm winters (high negative NAO indices) are generally associated with negative precipitation anomalies, while cold winters (high positive NAO indices) are accompanied by wetter than normal conditions. The identified inverse correlation between temperature and precipitation anomalies (although the year-to-year variability of precipitation is more than temperature because it is under the control of both thermodynamic and dynamic, see Shepherd, 2014) is primarily due to the fact that negative precipitation anomalies are in response to large-scale anticyclonic forcing, by which local positive temperature anomalies can be amplified.

Table 1
Population, the urban surface coverage and number of cars for 1000 people in the urban city of Tehran in some years since 1956. The data obtained from Shahraki et al. (2012), Asgharpour (2013), and Ghadami et al. (2013).

Year	Population	Surface area (km ^{2})	Number of private cars (for 1000 people)
1956	1,560,934	100	5
1966	2,719,730	181	25
1976	4,530,223	370	31
1986	6,058,207	620	61
1996	6,758,845	760	74
2006	7,711,230	800	90
2011	8,200,000		

5.2. Maximum and minimum temperature trends

On average, Tehran has been warming more significantly at night than in the daytime, such that its minimum temperature has been increasing at a rate three times greater than that of the maximum emperature. Statistically significant warming trend of the order 0.62 °C/decade has been observed for the minimum temperature, more than three times compared to 0.17 °C/decade for the maximum (Fig. 5). On the global scale, the increase rates of 0.204 and 0.141 °C/decade have been estimated for the minimum and maximum temperatures, respectively, for the period 1950–2004 (Vose et al., 2005). The increase of Tehran's minimum air temperature is substantially greater than the observed value on the global scale, while the rate of change in the maximum air temperature is nearly comparable to the increase rate of the global maximum air temperature. Much greater warming of the minimum air temperature than the maximum implies that the trend of the DTR is strongly negative, such that statistically significant average rate of −0.46 °C/decade has been identified (Fig. 5a), again substantially greater than the rate of −0.066 °C/decade identified on the global scale for the period 1950–2004 (Vose et al., 2005). Due to more significant warming of the minimum air temperature, the decrease rate of the DTR (−0.46 °C/decade) is greater than the rate of increase of the daily mean air temperature (0.37 °C/decade, see Fig. 3). As described below, the difference in the warming trends of the minimum and maximum air temperatures is mostly attributed to the land-use changes.

To better examine warming trends of the minimum and maximum air temperatures, statistical distributions of the winter minimum and the summer maximum temperatures at two 20-yr periods are displayed in Fig. 6, one covering the beginning of the series (1951–1970), and one the end (1994–2013). In general, nearly similar characteristics are identified for the distributions at the two time periods; however, comparison of the standard deviations of the distributions (not shown) indicate that the minimum air temperature is spread out over a wider range of values at the end of the period, implying its higher variability in recent years. In addition, shifts of the statistical distributions of both minimum and maximum air temperatures towards warmer

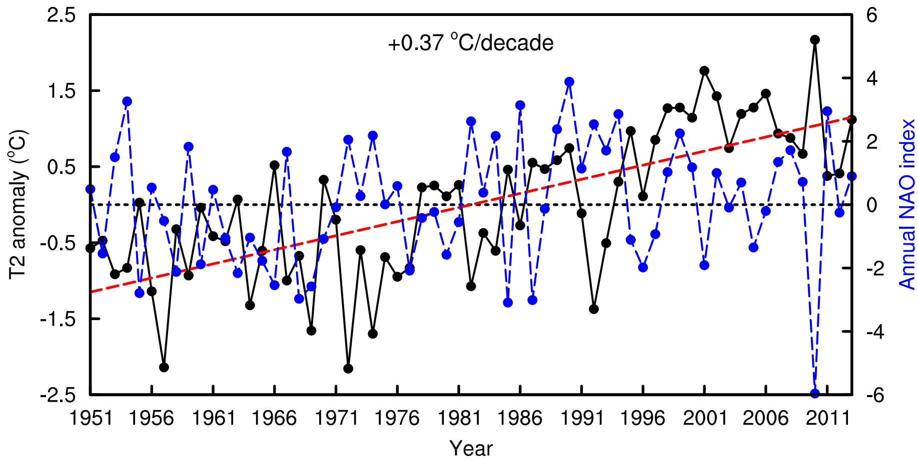

Fig. 3. Annual mean anomalies (relative to the mean for the period 1951–2013) of the near-surface air temperature (solid black line, °C) at Tehran Mehrabad airport. Dashed red line indicates the linear temperature trend and dashed blue line represents the North Atlantic Oscillation (NAO) index for the period 1951–2013. The temperature trend (0.37 °C/decade) is statistically significant at the 0.01 level.

temperatures are noticeable. The mean warming is much higher for the minimum air temperature as it has shifted by 2.5 °C towards warmer temperatures, compared to the maximum air temperature that has only shifted by 0.8 °C. As noted by Katz and Brown (1992); Schär et al. (2004), even small changes in the statistical distributions can lead to pronounced changes in the incidence of extremes, such as the observed record-breaking heat waves in 2010.

Changes in the maximum and minimum air temperatures over time can be manifested by inter-annual variations in the number of warm days and cold nights (Fig. 7), defined here as daily maximum air temperatures greater than 35.4 °C, and daily minimum air temperatures less than 0.5 °C, respectively. Two clear features are identified. Cold nighttime winter temperatures have become less common, while hot daytime summer temperatures have occurred more frequently in recent years. Changes in the number of cold nights are more significant than changes in the number of warm days. Indeed, the number of warm days has been rising at the rate of 2.7 per decade, while the number of cold nights has been decreasing at the rate of −6.7 per decade.

5.3. Seasonal variations in temperature trends

Different mechanisms regulate urban heat island effects and urban warming during winter and summer, which might lead to different warming trends in these seasons. During summer, urban asphalt absorbs, stores, and re-radiates more solar energy, which might lead to more significant daytime urban warming compared to winter. For example, results of (Cheng and Chan, 2012) indicated that the urban warming at the Pearl River Delta (PRD) region of China is more pronounced in summer than winter. Although, the urban warming by solar radiation is minimal in winter, other factors such as fuel combustion for home heating are contributed to the urban warming in winter. In addition, high levels of pollution in urban areas during winter can warm the urban area.

Table 2
Decadal anomalies (relative to the mean for the period 1951–2013) of daily mean, maximum and minimum near-surface air temperatures (°C) from 1950s to 2000s.

Decade	T2 anomaly	$T2_{min}$ anomaly	$T2_{max}$ anomaly
1950s	−0.81	−1.53	−0.22
1960s	−0.56	−1.02	0.02
1970s	−0.63	−0.6	−0.31
1980s	0.01	0.41	−0.26
1990s	0.35	0.88	0
2000s	1.15	1.7	0.78

The urban warming in winter and summer is examined in Tehran. On average, warming trends in the observed seasonally averaged daily mean air temperatures are nearly identical for winter and summer, with the rates of 0.35 °C/decade and 0.33 °C/decade (calculated from 3-hourly air temperatures), respectively (both of which are statistically significant); although inter-annual variability of air temperature is more pronounced in winter (Fig. 8). Differences of the winter mean air temperature from the long-term average range between −4.2 and 3.7 °C, while anomalies of the summer air temperature range between −2.2 and 1.7 °C. As Hansen et al. (2012) argued, a larger temperature variability in winter is owing to a greater latitudinal temperature gradient in winter, which allows temperature at a given place to vary considerably from year to year depending on whether the wind is from the south or north. In contrast, the difference of the air temperature between low and high latitudes is much smaller in summer, which provides less drive for exchange of air masses between middle and higher latitudes, and when exchange occurs the effect on temperature is less than that in winter.

In spite of nearly similar warming rates of the averaged daily mean air temperatures in winter and summer, our analyses indicate that the decrease rate of the DTR is stronger in winter (−0.54 °C/decade) than summer (−0.45 °C/decade), consistent with the results of Easterling et al. (1997); Vose et al. (2005) who identified the strongest decrease rate of the DTR in boreal winter and the least in summer on the global scale. Further analyses indicate that the rates of the increase of the minimum and maximum air temperatures are greater in summer (0.64 °C/decade and 0.19 °C/decade, respectively) than winter (0.58 °C/decade and 0.04 °C/decade, respectively).

6. Discussions

Our analyses indicate that Tehran has been warmed by the rate of 0.37 °C for the period 1951–2013 (Fig. 3), which is more significant compared to some other urban areas around the world (e.g. see Peterson, 2003). This could be due to the fact that Tehran is characterized by a rapid population growth and densely built-up area, although as Parker (2010) noted a different background climate may have also contributed. Indeed, as the climate of Tehran is mostly characterized by sunny days and clear nights, the city has had such a strong heat island effects.

Inter-annual fluctuations in the near-surface air temperatures of Tehran have been observed (Fig. 3), which are related to the year-to-year climate variability. Generally, under the positive NAO mode, colder conditions were prevailed in Tehran. On the other hand, negative values of the NAO index were generally associated with warmer conditions.

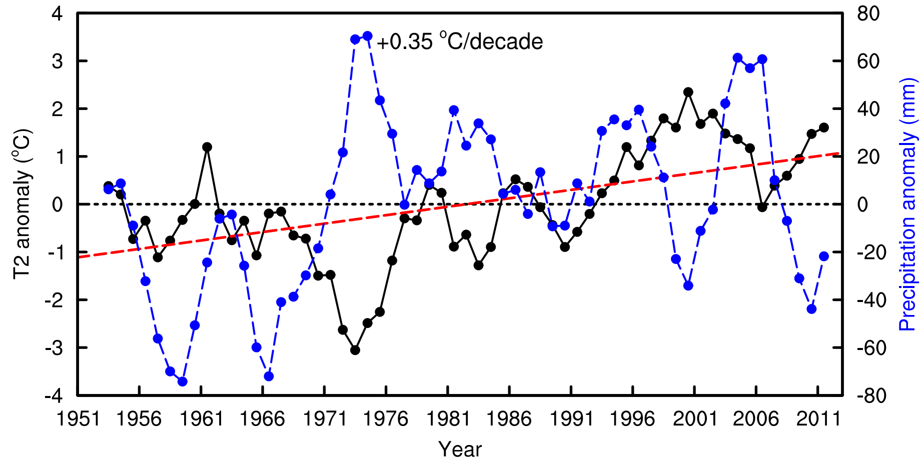

Fig. 4. Mean anomalies (relative to the winter mean for 1951–2013) of the near-surface air temperature (solid black line, °C) and precipitation (dashed blue line, mm) in winter (December–January–February) with a 4-year of smoothing at Tehran Mehrabad airport. Dashed red line indicates the linear temperature trend in winter for the period 1951–2013. The temperature trend in winter (0.35 °C/decade) is statistically significant at the 0.01 level.

For example, an unprecedented negative value of the NAO index in 2010 was associated with a record-breaking positive air temperature anomaly in Tehran, whereas extreme cold mean air temperatures in 1957, 1972, 1974 and 1992 (the year following the eruption of Mt. Pinatubo) were all associated with the positive NAO mode. However, few exceptions exist in our study. For example, the positive NAO mode in 1999 was associated with a higher than average annual mean air temperature anomaly. The correlation coefficient between the NAO index and the annual mean air temperature anomalies of Tehran has been found to be −0.37, but it is not statistically significant. Note that Fig. 3

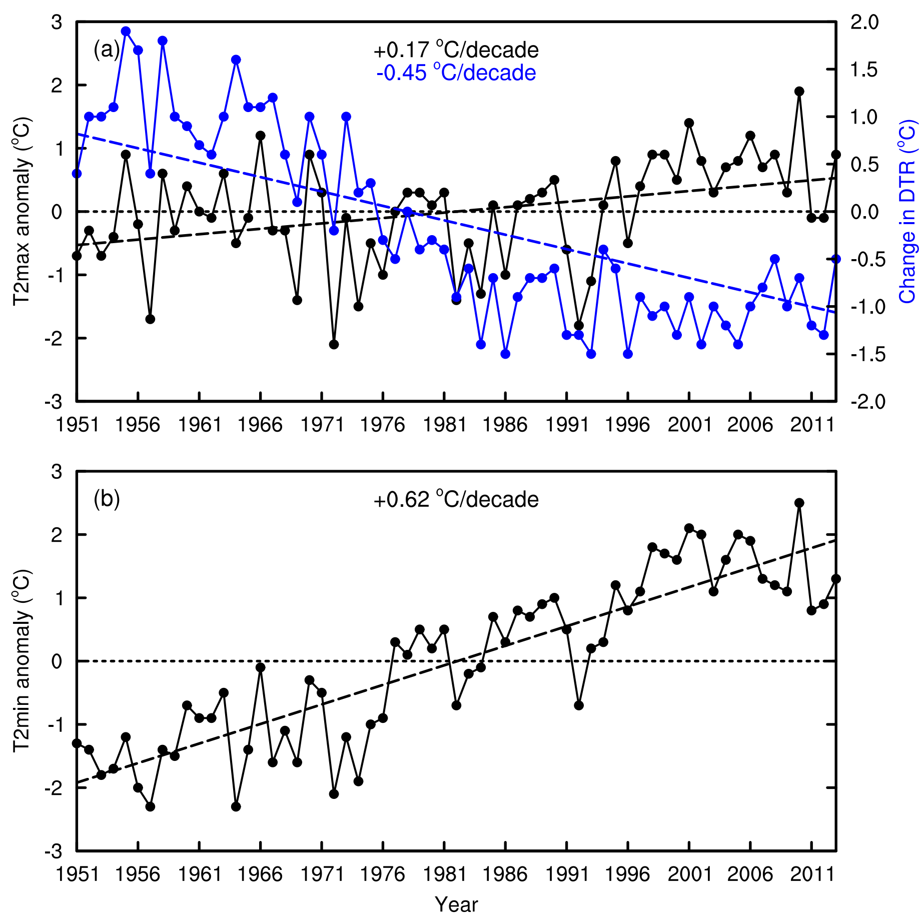

Fig. 5. (a) Annual mean anomalies (relative to the mean for 1951–2013) of the maximum near-surface air temperature (solid black line, °C) and changes in the diurnal temperature range (solid blue line, °C) at Tehran Mehrabad airport. (b) Annual mean anomalies (relative to the mean for 1951–2013) of the minimum near-surface air temperature (solid black line, °C). Dashed black lines indicate the linear maximum and minimum temperature trends, while the dashed blue line indicates the trend of the diurnal temperature range. All the trends are statistically significant at the 0.01 level.

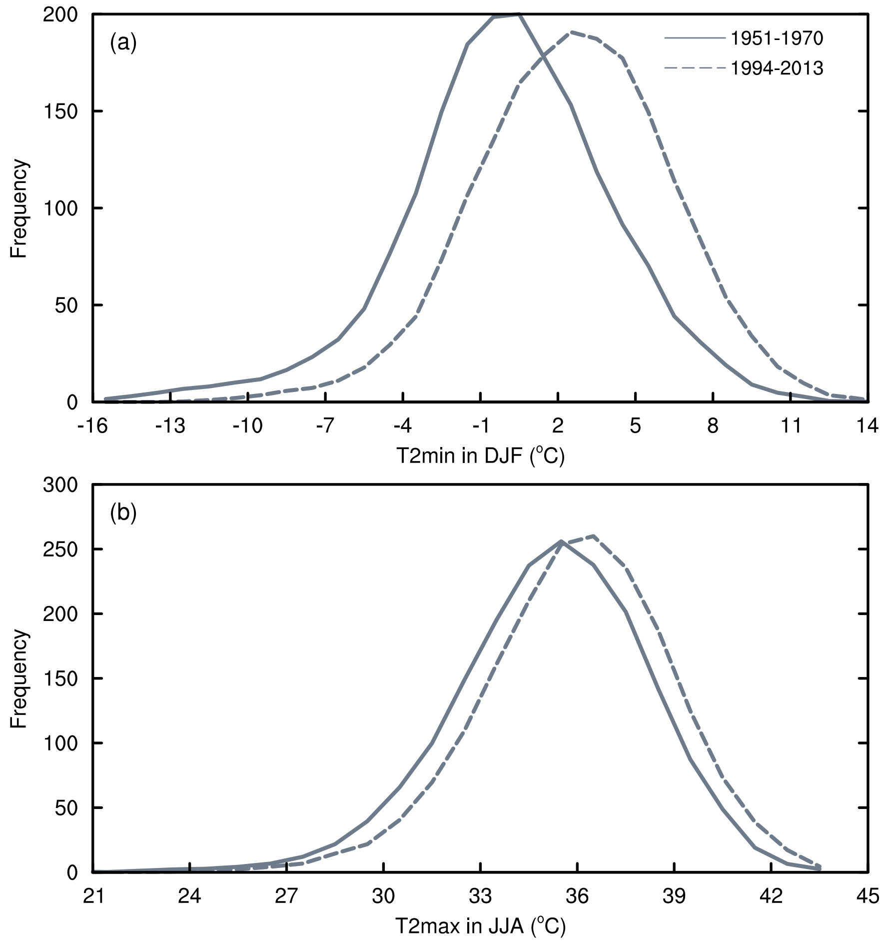

Fig. 6. Statistical distribution of the (a) winter (December–January–February) minimum, and (b) summer (June–July–August) maximum near-surface air temperatures (°C) with a 4-year of smoothing at Tehran Mehrabad airport for two 20-yr periods, one covering the beginning of the series (1951–1970, solid lines), and one the end (1994–2013, dashed lines).

indicates more positive NAO indices in recent years, and the NAO index has shifted towards a more positive mean state over the past 63 years, with nearly a +0.17 increase rate per decade. The shift towards higher NAO indices in recent years has been attributed to the anthropogenic warming (Intergovernmental Panel on Climate Change, 2007).

The identified much more increases in the minimum air temperature of Tehran compared to the maximum (discussed in the previous section, see Fig. 5) is consistent with previous studies conducted elsewhere. It is well established that in urban areas the surface warming is more pronounced on the minimum air temperature than the maximum (see for example, Karl et al., 1993) because at the time of minimum temperature, buildings and streets release the solar heating absorbed during the day, although anthropogenic heat sources (Childs and Raman, 2005; Kusaka and Kimura, 2004b), the obstruction of nighttime outgoing longwave radiation and, arguably, increases in the cloud cover (Karl et al., 1993) have also contributed. Therefore, urbanization and greenhouse effects act together at night, making the temperature higher than it would be in the absence of these two effects. On the other hand, mostly the greenhouse warming is present during daytime and the urban warming has little impact; yet one average, approximately half of the greenhouse warming is believed to be masked up by aerosols which have a cooling effect on Earth's climate (Ramanathan et al., 2005). The nighttime warming added by urbanization contributes to an increase in turbulent mixing near the surface, thereby increasing the land-atmosphere coupling (Seneviratne et al., 2006), causing additional warming of the near-surface air temperature.

In the analysis of the minimum and maximum air temperatures, the day-night difference in the stability of the boundary layer should be considered. In the stable boundary layer in the nighttime, vertical heat diffusion is much weaker than the unstable state in the daytime. Therefore, minimum temperature is not a measurement in a deep atmosphere where the impact of GHGs should be detected. Instead, it mostly represents temperatures of a shallow layer near the surface. Maximum temperature, on the other hand, represents the temperature of a well-mixed lower tropospheric layer, especially in summer. Therefore, it is a better measure of the greenhouse warming; although at the time of the maximum temperature, urban might have a cooling effect due to shading or a warming effect due to a greater absorption of radiation by the disturbed surface (and less evaporative cooling in response to less vegetation and exposed soil), previous studies (e.g. Argüeso et al., 2014) indicate that this daytime cooling or warming urban effects are slight.

Based on the above argument and the identified increase rates of the maximum and minimum air temperatures, we estimate that, for the daily mean warming trend of 0.37 °C/decade, approximately 0.17 °C/decade (the rising rate of the maximum air temperature (see Fig. 5a), approximately 46%) may have been caused by the greenhouse warming, and the rest (0.20 °C/decade, approximately 54%) by the land-use changes. This suggests that a larger portion of the temperature increase in Tehran over the last decades may have been caused by rapid urbanization rather than greenhouse effects. This is also manifested in the changes in the number of cold nights and warm days, such that the number of cold nights has been decreasing

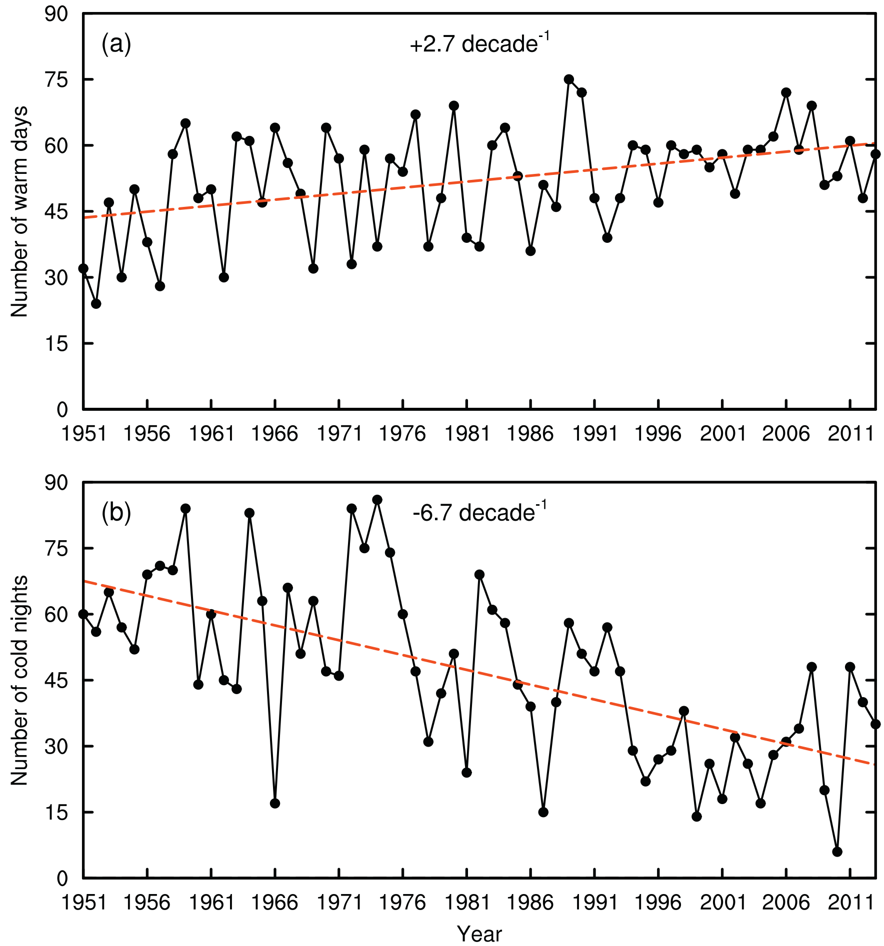

Fig. 7. Inter-annual variations in the number of (a) warm days (solid black line) and (b) cold nights (solid black line). Warm days and cold nights are defined here as daily maximum air temperatures greater than 35.4 °C (the long-term average of the maximum temperature for June–July–August and daily minimum air temperatures less than 0.5 °C (slightly less that the long-term average of the minimum temperature for December–January–February with the value of 0.9) at Tehran Mehrabad airport from 1951 to 2013. Dashed red lines indicate linear trends of the number of warm days and cold nights for the top and bottom panels, respectively. The trends are statistically significant at the 0.01 level.

more rapidly than the number of warm days (Fig. 7). As discussed above, more rapid reduction in the number of cold nights is attributed to the combined effects of urbanization and greenhouse warming, while mostly greenhouse warming has contributed to the increase rate of the number of warm days.

Seasonal variations in the DTR of the urban city of Tehran have been also examined. The DTR has been decreasing more rapidly in winter than summer because while the nighttime warming (which has been greater than the daytime warming) has not changed considerably from winter to summer, the daytime warming has been much stronger in summer, during which the solar radiation is stronger. It is expected that the rise of both minimum and maximum near-surface air temperatures to be greater in winter as the extra heat induced by urbanization would be stored on a shallow layer near the surface due to the dominance of thermally stable boundary layer which restricts turbulent upward heat transfer. However, more cloudy conditions in winter contribute to partly weaken the urbanization warming because both solar and outgoing longwave radiations are restricted by clouds.

7. Conclusions

Daily mean, maximum and minimum air temperature and precipitation records of a synoptic weather station at Tehran Mehrabad airport were obtained for a long-term period from 1951 to 2013, the period of an unprecedented increase in the concentration of GHGs and a rapid urbanization growth of Tehran.

Our observational analyses indicate that over the last 63 years, urbanization and increases in the concentration of GHGs have significantly warmed up the climate of Tehran, such that its average daily mean air temperature has been raised by 2.3 °C over the 63-yr period, and the increasing trend will likely continue under the urban growth and further increase of the locally and remotely emitted heat-trapping GHGs. The significant warming identified in the present study implies that the climate change signal is robust in the urban populated city of Tehran.

Statistically significant warming trend of the order 0.37 °C/decade has been observed during the entire period, while towards the end of the period, the warming trend has even further increased, reaching to the value of 0.48 °C/decade for the period 1983–2013, demonstrating a stronger warming in recent years. Our analyses (Figs. 3 to 5) suggest that the mid 1990s can be considered as the start of the most recent warming period observed in Tehran. The identified robust shift towards a warmer climate has resulted in an enhanced frequency of warm days, whereas the number of cold nights has been substantially reduced.

Warming trends of the maximum and minimum air temperatures over the 63-yr period were compared, for which 0.17 and 0.62 °C/decade rates of increase have been observed, respectively. In contrast to the more gradual increasing trend of the maximum air temperature, the observed

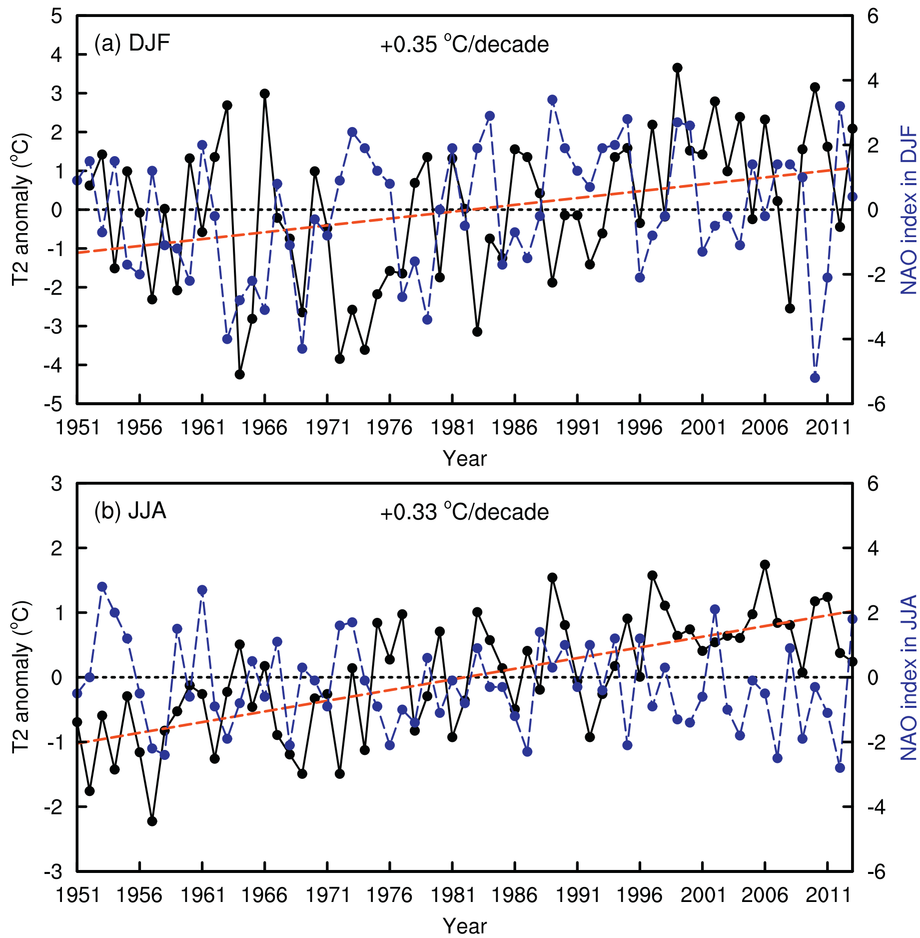

Fig. 8. (a) Winter (December–January–February) and (b) summer (June–July–August) mean anomalies (relative to the mean for the period 1951–2013) of the near-surface air temperatures (solid black lines, °C) at Tehran Mehrabad airport. Dashed blue lines indicate the NAO indices and dashed red lines indicate linear temperature trends in winter for the top panel, and summer for the bottom panel. The trends are statistically significant at the 0.01 level.

sharp increasing trend of the minimum indicates that Tehran's climate has been experiencing a pronounced increase in the nighttime temperature, suggesting that urbanization is mainly a nighttime phenomenon in Tehran. Therefore, a significant decrease in the number of cold nights (−6.7 per decade) and a lower rate of increase in the number of warm days (+2.7 per decade) have been observed. Furthermore, a decrease in the DTR as a result of urbanization has been observed. The strong contrast in the day-night temperature increase in the urban city of Tehran agrees with the general understanding that urban warming is more intense at night than in the day (Karl et al., 1984; Karl et al., 1993; McCarthy et al., 2010; Argüeso et al., 2014; Founda et al., 2015).

Warming trends of the urban city of Tehran from a seasonal perspective were also examined. In terms of the seasonally averaged daily mean air temperatures, the trend of wintertime warming has been almost similar to the summertime warming. However, inter-annual variability of the air temperature anomalies is larger in winter than summer, primarily due to greater latitudinal temperature gradients in winter. Furthermore, a seasonal cycle in the changes of the DTR was identified, with less decrease rate of the DTR in summer.

The present study highlights the occurrence of drastically different nighttime and daytime temperature changes in response to urbanization effects. The identified significant local warming and different rates of warming in day and night due to urbanization suggest that currently missing urbanization warming should be considered in the climate models. The results of our analyses are limited because temperature trends in the urban city of Tehran are indicated by a single meteorological station which is an incomplete representation of temperature changes across a large geographic zone.

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