Global NEST Journal, Vol 19, No 4, pp 666-673

Effect of aerosols on different regime of clouds and their precipitation over Tehran city

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Received: 19/01/2017, Accepted: 27/11/2017, Available online: 06/12/2017
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Abstract

In this study we investigate the impact of aerosols on different cloud regimes and amount of their precipitation over Tehran for the period of 2003-2014, utilizing data from Moderate-Resolution Imaging Spectroradiometer (MODIS), Tropical Rainfall Measuring Mission (TRMM) and surface data from local synoptic stations. The regimes were determined using a k-means clustering method on retrieved cloud properties. The results indicate that in mixed clouds, increase in aerosols has led to increase in the mean cloud effective radius (CER), cloud height as well as lighting and precipitation amounts of weak and moderate convective cells which may be attributed to more freezing of cloud droplets above the 0 °C isotherm and its associated latent heat releases. Vice versa, warm clouds intensity in polluted air condition are weeker than clean air condition. The results also showed that, nimbostratus clouds thickness and their precipitation increase under high aerosol index (AI). Both TRMM and rain gauges data, however, showed that the average amount of precipitation has decreased during polluted episodes in comparison with clean episodes during the period of study. Elaborating on the observed overall changes in the amount of precipitation, it may be concluded that over Seeding was a critical factor in reducing the mean precipitation over Tehran. Also, observed differences on clouds microphysics over different parts of the city may be related to local pollutions, type of ambient air aerosols and topography conditions.

Keyword: Aerosol, Regime of cloud, k-means clustering, MODIS, TRMM, Tehran, Lighting.

1. Introduction

Not only have clouds and precipitation (snow, rain and hail) allocated an important part of the subsystem atmospheric phenomena of terrestrial climate, but are also considered as the main components of the water cycle. Aerosols play an important role in cloudiness and precipitation. In warm clouds with the same liquid water path, increase in aerosols concentration results in the reduction of effective radius of cloud droplets and increase of cloud albedo that is referred to as "first indirect effect" or "Twomey effects" (Twomey, 1977; Twomey *et al.*, 1984). Variation in concentration of aerosols causes variation in the thickness, life period and precipitation rate of the clouds, referred to as "second indirect effect" or "Albrecht effect", (Albrecht, 1989; Hansen *et al.*, 1997; Ackerman *et al.*, 2000). So far, the majority of precipitation studies and numerical simulations in aerosol-cloud-precipitation interaction have shown that concentration increase of aerosols causes the reduction of the warm clouds amount and their precipitation due to droplets size reduction besides collision and their coalescence (Squires and Twomey, 1961; Warner & Twomey, 1967; Warner, 1968; Rosenfeld, 1999). In contrast, in cold clouds, an increase in the concentration of aerosols resulted in increase in the rate of droplets freezing and the release of more latent heat above the zero degree isotherm and eventually the increase of hail stones (Rosenfeld and Woodley, 2000), precipitation rate, clouds top height and formation of large anvils (Lin *et al.*, 2006; Andreae *et al.*, 2004). Despite, the large number of field experiments and numerical studies in this field, there are still ambiguities involved with our understanding of aerosol-cloud-precipitation interrelationship, especially in the mixed-phase clouds. The complexity is that high that even in one type of clouds and over a specific area different results have been achieved. For example, some studies upon the precipitation from convective clouds indicates that increase in aerosols concentration will lead to the reduction of the amount of precipitation from these types of clouds (Rosenfeld 1999; Huang *et al.* 2009; Sorooshian *et al.*, 2009; Joos *et al.*, 2017; Sarangi *et al.*, 2017). Although some other studies by means of space and ground based remote sensing show increase in the amount of precipitation from convective clouds (Li *et al.*, 2011; Koren *et al.*, 2012; Niu and Li, 2012; Joos *et al.*, 2017; Sarangi *et al.*, 2017). It is argued that observed differences among the results of different studies may be related to the meteorological and thermodynamic conditions, mixed phase cloud type, air masses characteristics, applied data acquisition and analysis methods (Gultepe *et al.*, 1996; Cahalan *et al.*, 2001; Pawlowska and Brenguier, 2003; Comstock *et al.*, 2004; Loeb and Manalo-Smith, 2005; Mauger and Norris, 2007; Loeb and Schuster, 2008; Kubar*et al.*, 2009; Grandey and Stier, 2010; Su *et al.*, 2010; Duong *et al.*, 2011; Sarangi *et al.*, 2017). Accordingly, it may be suggested that a primary study upon the cloud regimes over any region prior to the study on the aerosol-cloud-precipitation interrelationships, may lead to better and more accurate results.

In this article, we studied the effects of aerosols on different cloud types and their precipitation over the industrial and populous city of Tehran with minimum errors. To investigate the impact of aerosols on different regimes of cloud and their precipitation, the cloud observations from conventional network of weather observing systems and satellites such as cloud type, cloud top pressure (CTP) and cloud optical thickness (COT) for the period of 2003-2014 were used to classify the clouds by means of the K-means clustering method. Likewise, spatial variations arising from role of aerosols on the microphysics of clouds in the five key points of Tehran city in polluted and clean conditions have been studied.

2. Study area

In this article, we studied the effects of aerosols on clouds and precipitation over the Tehran city. The city of Tehran (fig. 1), the capital of I. R. of Iran, is a mega-polis with more than 10 million populations. The city long term annual average precipitation is 300 mm. Tehran rainy season starts at the middle of the autumn and ends in the middle of the spring. This does not mean there is no precipitation during other parts of the year, but if it rains it will not be that significant and it is mostly a trace.

Considering city geographical conditions, location of industrial units and factories, local wind field, precipitation temporal and spatial distributions and long-term precipitation records, two synoptic stations Mehrabad and Aghdasieh were selected for evaluation in this study. Figure 1 shows information about the geographical location of the two stations within the city. Aghdasieh synoptic station which started to record data in 1988 is located in the northeast of Tehran, the area with highest annual average of precipitation among other areas of the city.

According to Iranian Meteorological Organization records, the annual average of precipitation in this area is 420mm. Mehrabad synoptic station is the oldest meteorological station of the city that started to work in 1951. The station located in Mehrabad airport at the west of Tehran. Considering the distribution of the industrial units and factories, buildup areas, aerial and ground traffics and transportations, local daily atmospheric circulation, and the station geographical location, it could be claimed that the station is prone to substantial periods of air pollution from both topographic and anthropogenic point of view. The annual average of precipitation over this station is 231mm.

3. Data and methodology

In this study, the influences of aerosols on cloud and precipitation during the years 2003-2014 were studied in Tehran and its surrounding area (36^0N-33^0S; 49^0W- 53^0E). In this research, the Moderate-resolution Imaging Spectroradiometer (MODIS) of aerosol, cloud data[1] and daily precipitation data of Tropical Rainfall Measuring Mission (TRMM) satellite (3B42-V7) as well as daily data related to synoptic stations were applied. Table (1) shows the temporal and spatial specifications of all the terrestrial and satellite data that have been used in this paper.

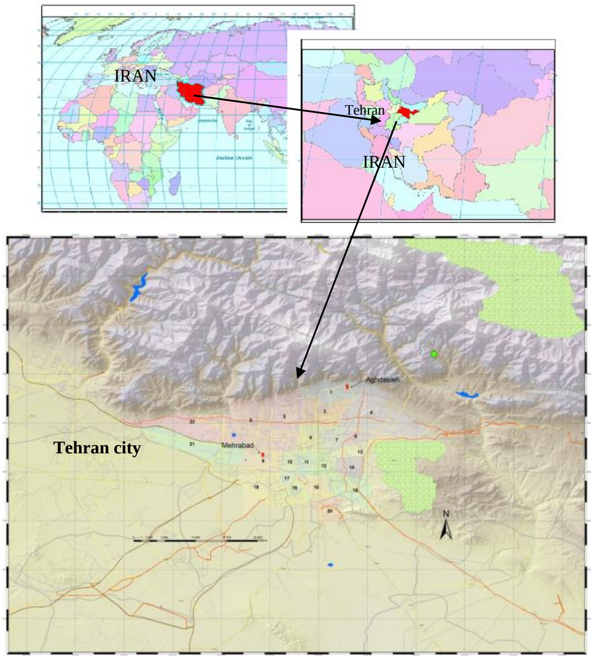


Figure 1. The Location of Tehran city, and the stations Mehrabad and Aghdasieh of Iran Meteorological Organization

The precipitation amount obtained via remote sensing data demonstrates the spatial distribution of precipitation much better than rain gauge data, but these data types have several errors (Berg *et al.*, 2006; Bauer *et al.*, 2005). In some cases, microwave scanners of these satellites measure ice crystals in the clouds peak, atmosphere and soil humidity, coarse cloud particles and severe pollutions of aerosols instead of rain droplets. In order to obviate errors, in this study the average daily precipitation data of rain gauges of Tehran (Aghdasieh & Mehrabad synoptic stations) as well as daily precipitation data of TRMM satellite are used for validation.

For clouds classification, the MODIS data on board Aqua satellite (MYD08-D3-V5.1), which passes at about 13:30 local time of Tehran, were used. Considering the transmission time of aqua satellite over Iran the top of the boundary layer reached about 2 km and aerosol particles are generally well mixed (Del Guasta, 2002; Huang *et al.*, 2008; Campbell *et al.*, 2013). In this section of the article, Aeroaol Index (AI) (Aerosol Optical Depth (AOD) multiplied by Angstrom Exponent[2] (AE)) was used as a proxy for the cloud condensation nuclei (CCN) since AI represents both

[1] (cloud effective radius (CER), cloud top temperature (CTT), cloud top pressure (CTP), cloud water path (CWP), cloud optical thickness (COT), cloud fraction (CF), cloud phase)

[2] Angstrom Exponent: A measure of the spectral dependence of Aerosol Optical Depth. MODIS atmospheric science team provides Angstrom exponent for the aerosols over Land based on 470 and 660 nm optical depths (QA-weighted).

aerosol amount and their size (Nakajima 2001; Breon *et al.*, 2002; Levy *et al.*, 2007 & 2010; Penner *et al.*, 2012; Gryspeerdt et al, 2012), thus it is a more appropriate alternative in comparison to the AOD for CNNs. Two independent algorithms are applied to retrieve aerosol properties: the Deep Blue method over land using reflectance at 0.47, 0.66, and 2.13 µm and the dark target method over ocean using seven bands ranging from 0.47 to 2.13 µm (Remer *et al.*, 2005, 2008; Levy *et al.*, 2010). The Deep Blue algorithm is most appropriate for land. This algorithm rectifies unwanted effects due to clouds, albedo, snow, etc., (Remer *et al.*, 2005; Levy *et al.*, 2010) and therefore is a suitable algorithm for this research.

Table1. Summary of temporal and spatial characteristics of datasets as well as sources of data, were used

(a)Ground data

Station Name	Latitude	Longitude	Elevation(M)	Data Type	Date Range & Sources of data
Mehrabad (Urban(airport))	35^0 41'	51^0 19'	1190.8	*Precipitation(mm), lighting, visibility(m), AQI index($PM_{2.5}$)*	1/1/1951–31/12/2014 *Meteorological organization of Iran.*
Aghdasieh (Urban)	35^0 47'	51^0 37'	1548.2	*Precipitation(mm), lighting, visibility(m), AQI index($PM_{2.5}$)*	1/1/1988–31/12/2014 *Meteorological organization of Iran.*

(b)Satellite data

Product	Dataset	Horizontal Resolution	Date Range	Sensor (satellite) & sources of data
Precipitation (3B42-V7)	*Rain rate (mm/h)*	$1^0 \times 1^0$	1/1/2003–31/12/2014	TRMM https://giovanni.gsfc.nasa.gov/giovanni/
Humidity (MOOD05-L2 & MYD05-L2)	*Water Vapor near infrared*	1 km	1/1/2003–31/12/2014	MODIS (Aqua and Terra) https://reverb.echo.nasa.gov/reverb/
Cloud (MYD06-L2 & MOD06-L2) And (MYD08-D3-v5.1)	*Cloud Optical Thickness* *Cloud Water Path (g/m²)* *Cloud Effective Radius (microns)* *Cloud Top Pressure (h Pa)* *Cloud Top temperature (^{0}K)* *Cloud Fraction* *Cloud phase*	1 & 5 km and $1^0 \times 1^0$	1/1/2003–31/12/2014	MODIS (Aqua and Terra) https://reverb.echo.nasa.gov/reverb/ and MODIS (Aqua) https://giovanni.gsfc.nasa.gov/giovanni/
Aerosol (MYD08-D3-v5.1)	*Aerosol Optical Depth* (550 nm-Deep blue algorithm) *Angstrom Exponent* (470 / 660 nm)	$1^0 \times 1^0$	1/1/2003–31/12/2014	MODIS (Aqua) https://giovanni.gsfc.nasa.gov/giovanni/

In this study the cloud classifications have been done based on the same method as Gryspeerdt and Stier (2012). This method was used to determine cloud regimes for the International Satellite Cloud Climatology Project (ISCCP) (Rossow *et al.*, 2005; Williams and Webb, 2009). The clouds were grouped for 2003-2014, with the help of daily data quantifications of Cloud Top Pressure (CTP) and Cloud Optical Thickness (COT) with the aid of K-means clustering method (Anderberg, 1973). To determine the number of clusters for k-means cluster analysis, the function was driven from the Gryspeerdt and Stier (2012) method. After clouds clustering, variations in the precipitation amount in each cloud regime, were studied and compared for both clean and polluted conditions (in terms of aerosols amount). In order to reduce the errors due to correlation of AI-CF (Gryspeerdt *et al.*, (2014), the same amount of cloud fraction in both clean and polluted conditions has been selected. In order to investigate the local impacts of aerosols on cloud and precipitation, the average daily precipitation data of rain gauges of Tehran as well as daily precipitation data of TRMM satellite are used for validation.

In order to enhance the accuracy of the study, several case studies have been carried out using AQI index related to suspended particles less than 2.5 micro meters with resolution of 1*1 km and the visibility data related to synoptic stations were selected as the proxy for CCNs. The 36 cases from cold and warm clouds for the period of 2003-2014 were selected. The some cases, one occurred in the days preceding the precipitation occurrence and during the precipitation, during which high AQI index related to suspended particles less than 2.5 microns and low visibility were selected. The other cases that had a similar occurrence period, synoptic pattern, relative humidity in 850hPa level, direction and amount of wind were selected and compared with two precipitation event cases in polluted condition. All of these facts were obtained from the NCEP / NCAR reanalysis). Precipitable water (MOOD05-L2 & MYD05-L2) and cloudiness fraction with these events, but had low AQI index values and high visibility. For the study of cloud microphysics the average data of MODIS on board Aqua and Terra satellite (MOD06-L2 &MYD06-L2) were applied. In order to extract MODIS data, the ERDAS-V13 software was used. The MODIS cloud values were studied one day prior to the precipitation, on the day of precipitation itself and one day after the occurrence of precipitation and have been exploited for both regions.

4. Results and discussion

4.1. Regime-based analysis of aerosol-cloud-precipitation interactions (2003-2014)

The grouping results of Tehran city clouds during the years 2003 – 2014 along with centroid values of CTP, CTT, COT and CF in each cloud regime also, Frequency of cloud's regime were written in table (2). As is observed in table (2), with this method, the clouds have been divided into 6 regimes. The regimes 1, 2 and 6 belonged to stratus clouds and regimes 3, 4 and 5 belonged to convective clouds respectively. Results show that weak and deep convective clouds have the highest frequency for the period of study.

Table 2. Properties of the regime centroids (CTP, COT, CTT, CF%, Frequency of cloud's regime) used in this study, (2003-2014)

Regime	CTP (hpa)	COT	CTT (K)	CF%	Frequency
1-nimboStratus	570.07	20.25	264.09	45	176
2-Stratus(weak)	758.75	17.5	272.28	40	369
3-Moderate convective	383.4	17.91	241.55	70	391
4-Deep convective	285.13	10.68	227.42	80	550
5-Weak convective	473.20	19	253.89	55	570
6-Stratocumulus; Altostratus; Altocumulus	658.25	22.94	267.95	47	440

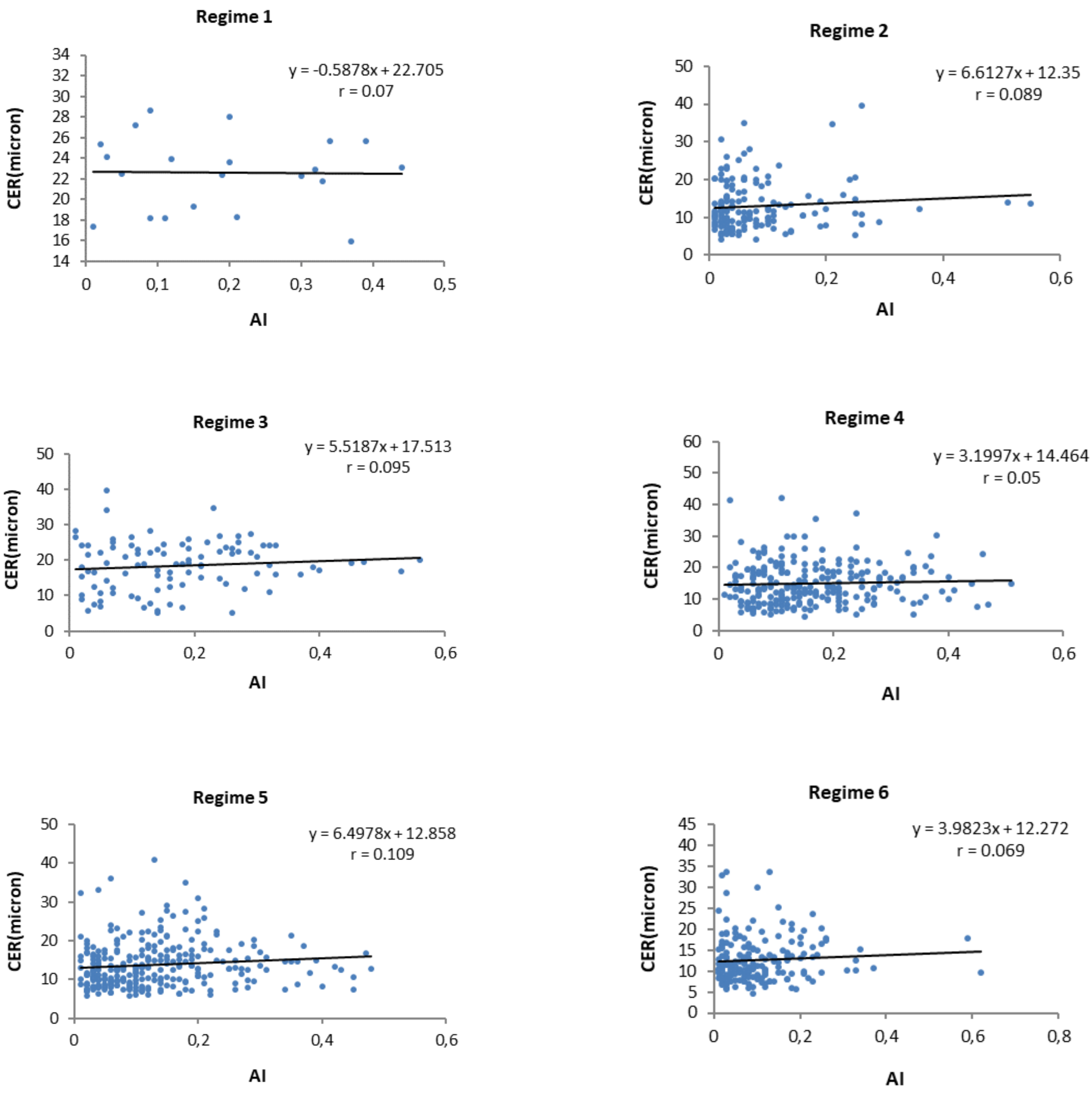
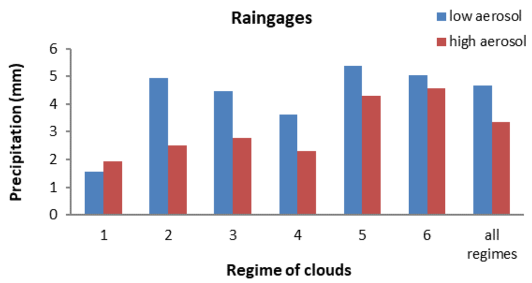


Figure 2. Scatter diagram between AI and CER for different regime of clouds (2003-2014)

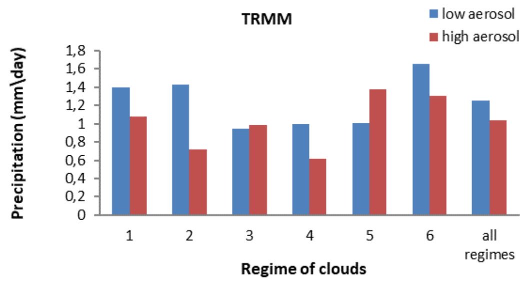
For the study of the initial indirect effect in each regime, scatter plot diagrams between CER with AI were drawn in Figure (2) for each regime.

Only a positive and significant correlation was observed in regime 5 clouds, whereas no significant correlation was observed in the remaining regimes. Considering the type of regime 5 clouds and also the elevated average temperature of clouds, it can be concluded that these clouds were related to mixed type. Considering the majority of conducted studies increase of CCN in the convective type clouds caused an increase in the formation of ice crystals and consequently, increase of freezing latent heat release above the zero degrees Celsius level. Hence, the significant and positive correlation in convective clouds had a viable concurrence with the majority of the similar studies and observations in the other regimes of the world (Rosenfeld and Woodley, 2000; Williams *et al.*, 2002; Lin *et al.*, 2006; Bell *et al.*, 2008).

The 12-year average precipitation amount that was calculated from rain gauges as well as TRMM satellite data, in the low and high aerosol conditions were calculated for six cloud regimes and also in the state without grouping which were drawn as a histogram in the Figure 3-a and 3-b. As it is observed from charts, the 12-year average precipitation amounts that were obtained from data of rain gauge stations in the state without grouping as well as five groups (2, 3, 4, 5 and 6) in low aerosol condition in relation to the high aerosol condition was higher. Only in regime 1, that corresponds to Nimbostratus clouds, the mean of precipitation in terms of high AI were obtained at a slightly higher value in relation to the low aerosol condition. This result showed that an increase of aerosol concentration causes for invigoration of Nimbostratus clouds. However, the mean of precipitation from TRMM satellite, for the groups 3 and 5 showed the increased precipitation in polluted condition in relation to a clean condition. In other words, weak and moderate convective cloud types and their precipitations during these years were invigorated with increased aerosols. Since data of satellites showed much better local distribution of precipitation amount in comparison with rain gauges and convective clouds, the results obtained from the TRMM satellite could be considered correct. For determining the validity of this matter, the lightning data of the Aghdasieh and Mehrabad synoptic stations of Iran, was used.



(a)



(b)

Figure 3. Mean precipitation amount in six different regimes of clouds as well as without grouping were obtained for the cases of high and low AI, for the period of 2003–2014. Daily precipitation data were obtained from (a) rain gauges and (b) TRMM satellite

Initially, the codes related to lightning along with their occurrence dates in each of the two stations were derived from synoptic data. Later, the number of lightning with weak and medium intensity, were counted annually for the two stations. In Figure (4), scatter diagram was drawn between annual accumulative lightning associated with precipitation that were of weak and moderate intensity (aggregate of two synoptic stations) and annual averages of AOD (MODIS scanner data average). There is positive correlation between them (r=+0.55). This matter is revealing the direct effect of aerosol concentration on the number of lightning occurrence also the validity of TRMM satellite data results. Considering the entire obtained results, it can be safely concluded that over seeding is one of the important and essential factors in the reduction of cloudiness and consequently decline of 12-year average total precipitation amount.

4.2. Case study

To study cold and warm cloud microphysics over five region of the city, seven factors of COT, CWP, CTP, CTT, CER, CF and cloud phase parameters have been studied for one day before precipitation (0), the day precipitation started (1), and the continuation of precipitation (2). Results concerning COT, CTT, CTP, CWP and CER means are shown in Tables (3-a and 3-b). In cold clouds (table 3-a), Comparison of CER between clear air and polluted air condotions showed that it is very smaller for polluted air before precipitation. It may be related to the cloud overseeding

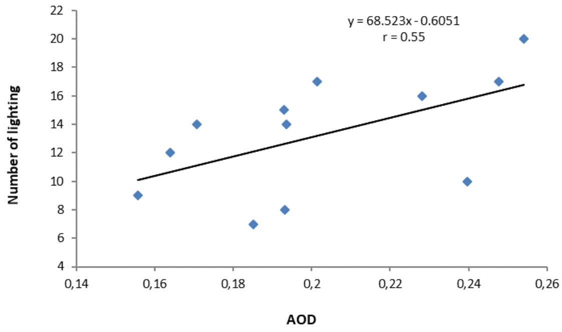


Figure 4. Scatter diagram between total of annual lightning numbers with weak and moderate intensity and annual means of AOD (2003-2014)

Table 3. Mean of CTT, CTP, CER, CWP and COT, for events of precipitation were studied for five region of Tehran city (north-east (NE), north-west (NW), south-east (SE), south-west (SW)). Numbers 0, 1 and 2 are an indication of one day before precipitation, the day precipitation started and the continuation of precipitation, respectively. (a)Cold clouds and (b) warm clouds.

(a)Cold clouds		*CTT (K)*			*CTP(hpa)*			*CER(micron)*			*CWP(g/m²)*			*COT*		
		0	**1**	**2**	**0**	**1**	**2**	**0**	**1**	**2**	**0**	**1**	**2**	**0**	**1**	**2**
high aerosol	*NE*	256.6	233.9	253.4	555	360	460	6.8	24.9	25.4	50	1523	20	12.3	100	0.8
	NW	291	261	236	440	555	450	11	17.9	21	313	100	122	50	8	10
	SE	292.0	262.6	237.7	450	560	458	4.6	25.1	25	313	85	118	3.9	14.4	8
	SW	268.9	235.6	258.5	685	375	555	5.4	27.1	25.7	18	480	89	7.3	28.5	5.6
	C	276.6	235	275.9	800	375	800	5.9	21.6	15.3	49	1357	26	9	100	0.6
low aerosol	*NE*	240.2	266.2	276.2	345	555	712.3	25	7.7	13.3	69	37	99	4.5	7.55	9.8
	NW	255.1	260.9	256.0	405	620	595	33	23.1	10.1	52	72	181	8	26	27
	SE	223.5	261.2	243.5	260	825	480	14	24.2	27.2	30	60	156	8	17.3	9.8
	SW	242.8	284.2	275.2	360	730	712	25	19.2	13.3	30	26	99.1	2.3	2.08	11.5
	C	247.9	259.3	247.9	427	620	515	26	21.9	18.1	80	32	145	9	22	12.7
(b)warm clouds		*CTT (K)*			*CTP(hpa)*			*CER(micron)*			*CWP(g/m²)*			*COT*		
		0	**1**	**2**	**0**	**1**	**2**	**0**	**1**	**2**	**0**	**1**	**2**	**0**	**1**	**2**
high aerosol	*NE*	280.6	287.1	288.4	605	700	790	12	10	13	40	37	45	6	27	12
	NW	279.6	287.1	287.4	640	709	710	15	11	15	53	40	50	8	26	27
	SE	282.6	288.1	287.4	650	750	890	7	5	9	45	53	56	9	12	9.8
	SW	280.6	288.5	287.4	675	720	790	7	8	9	50	26	50	6	16	11.5
	C	282.6	288.3	288.4	600	745	700	9	7	11	50	32	60	9	22	12.7
low aerosol	*NE*	278.6	290.1	280.4	845	755	755	30	29	28	89	155	70	40	99	30
	NW	277.7	280.1	281.4	825	750	770	29	29	26	98	130	82	50	100	40
	SE	279.6	281.7	282.4	860	800	810	19	20	19	90	123	98	30	80	38
	SW	280.9	281.1	282.4	860	830	830	22	19	17	18	180	89	37	88	40
	C	282.6	282.2	282.4	827	770	810	23	19	20	49	150	86	50	100	45

In severe particle Pollution, especially in the southeast, southwest and central regions of Tehran a sharp decline in the amount of CER (less than 4.5 microns) was seen before event of precipitation. After precipitation begins, CER increases maybe seen as a result of cloud condensation nuclei reduction due to the washout by precipitation. At this time, CER surpasses its amount during clear air condition. The study also revealed that COT, CWP, and cloud top height were higher in polluted air conditions than clear air condition. The same results were reported by some other authors (Rosenfeld and Woodley, 2000; Orville *et al.*, 2001; Williams *et al.*, 2002; Andrea *et al.*, 2004; Lin *et al.*, 2006; Bell *et al.*, 2008). In similar systems, COT, CWP, CER and cloud top height over northwest and northeast of city were higher than southwest, southeast and central parts of Tehran. Thus, role of local pollutions, type of ambient air aerosols and topography conditions were the most important factors in variation of cloud microphysics. From the studied cases it could be concluded that the amount of CER, COT, and CWP air varies between 4.6-27 μm, 8-100, and 30-1523 g/m^2, respectively. In warm clouds (table 3-b), increase in aerosols concentration results in the reduction of CER, CWP, COT and cloud top height (Twomey, 1977; Twomey *et al.*, 1984) and their intensity in polluted air condition are weeker than clean air condition.

5. Conclusion

In this study, the influences of aerosols on different regimes of cloud and their precipitation during the years 2003-2014 utilizing ground based and satellite data were studied in Tehran. The main results as following:

1-Both TRMM and rain gauges data showed that the mean amount of precipitation has decreased during polluted episodes in comparison with clean episodes during the period of study (2003-2014). Only, nimbostratus, weak and moderate convective clouds had shown that clouds thickness and mean amount of precipitation increase under high AI. Elaborating on the observed overall changes in the amount of precipitation, it may be concluded that over seeding was a critical factor in reducing the mean precipitation over Tehran.

2- Convective clouds had the highest frequency among all clouds. There were positive correlations between aerosols concentration with CF, CER, cloud top height, number of lighting and precipitation amounts.

3- In severe particle Pollution, especially in the southeast, southwest and central regions of Tehran a sharp decline in the amount of CER (less than 4.5 microns) had occurred before event of precipitation. In similar systems, cloud top height, COT, CWP and CER over northwest and northeast of city were higher than southwest, southeast and central parts of Tehran. Cold clouds intensity in polluted air conditions are higher than clear air condition. Vice versa, warm clouds intensity in polluted air condition are weeker than clean air condition.

4-The role of local pollutions, type of ambient air aerosols and topography conditions were the most important factors in the variation of cloud microphysics.

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