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Seasonal Study of Dust Deposition and Fine Particles (PM 2.5) in Iran Using MERRA-2 Data

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Abstract

The research results indicated that wet and dry dust deposition is a function of geographical characteristics. The seasonal wet and dry dust deposition and Fine Particles (PM 2.5) correlation in Iran with elevation, latitude and longitude results that the maximum correlation belongs to height, followed by latitude and longitude; meanwhile height and latitude are strongly and reversely correlated with each other. The Regional ratio of dry to wet deposition indicated that the share of dry deposition was high in south-eastern and western regions of Iran indicating the distance from dust sources. Wet and dry deposition fluxes of mineral dusts were both high in spring and summer low in clod season, showing similar seasonal variations to frequency of Aeolian dust events in Iran. The high amount of wet deposition in summer and autumn in northern regions (Mazandaran and Gilan Provinces) is due to the sea salt and anthropogenic factor dust that is washed out by local precipitation. Relatively high concentration of Fine Particles (PM 2.5) with different compounds in Iran is due to two factors: natural particles (mineral dust and sea salt) and anthropogenic activities (fossil fuel and biofuel). The maximum value of PM 2.5 can be seen in the south and southwestern regions of Iran due to local and trans-regional sources of sand and dust storms (SDS).

Keywords: Atmospheric Pollution, Dust Deposition, Fine Particles (PM 2.5), MERRA-2, Iran

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1 Introduction

Dust particles, as a major component of aerosols, play a crucial role in meteorological feedback and bio-geochemical cycles (Shao et al., 2011; McTainsh & Strong, 2007). Therefore, it is necessary to increase awareness concerning the impact of atmospheric mineral dust particles on the Earth's physical processes and biosphere. The meteorological and climatic significance of dust particles can be categorized into the energy balance of the Earth's atmospheric system, changes in the dynamics and chemistry of the atmosphere on regional and global scales, absorption and diffusion of radiation in the atmosphere, microphysical changes in clouds and their radiant properties (IPCC, 2013), and changes occurring at snow and ice levels. Increased provision of mineral nutrients in marine environments and increased growth of marine phytoplankton are among the positive aspects of dust (Al-Shehhi et al., 2014). Furthermore, these particles can, on a regional scale, reduce air and soil quality (e.g., soil contamination by heavy metals), reduce visibility and affect land and air traffic, exacerbate drought conditions, directly affect human health (lung cancer, respiratory problems, etc.), and even influence the solar energy industry through deposited photovoltaic panels (Giannadaki et al., 2014; Gherboudj & Ghedira, 2016; Gherboudj et al., 2017).

More than 90 percent of dust particles in the Earth's atmosphere are from the desert regions of northern Africa, Middle East (including Central Asia), and Asia (including China and Mongolia), with almost 60% from northern Africa (Chin et al., 2007), including six great deserts, namely the Sahara Desert in Africa, the Arabian Desert in the Middle East, Taklamakan and Gobi deserts in China and Mongolia, the Thar Desert in the Indian subcontinent, and Karakum Desert and Kavir Desert in Central Asia.

Iran has encountered many problems in recent years, as it is located on the dust belt, which originates from the western coast of northern Africa, passes through the Middle East and Central and South Asia (Goudie & Middleton, 2006). Therefore, the investigation of dust, especially its new features, to better understand this phenomenon and deal with it, is indispensable.

The deposition of dust depends on various factors such as meteorological conditions on the vicinity, physicochemical properties of dust particles, and the nature of the earth surface (Wesely, 2007). The study follows two main objectives: First, to identify dry and wet deposition as the dust load in Iran; second, to assess the pollution caused by it using the Fine Particles (PM 2.5) index.

The results of this study will aid in understanding the characteristics of the long-term variability of PM 2.5 in, and they will also have implications in designing effective strategies to mitigate health damage caused by air pollution in Iran.

The dust particles in the atmosphere falling on the surface can be categorized into two general types: 1) wet deposition, and 2) dry deposition. The dry deposition process consists of three parts: 1- Aerodynamic transport and gravitational sedimentation, 2- Brownian transport, and 3- Uptake at the surface (Seinfeld and Pandis, 2012).

The main mechanism for separating aerosols from the atmosphere involves the dry and wet deposition processes. The presence duration of aerosols in the atmosphere depends on the dispersion properties of the particle and weather conditions, fluctuating between days and a week (Lazaridis, 2011). In many studies into atmospheric, environmental, and epidemiological pollutions, fine particulate matters (PM2.5, more specifically, suspending particles with an aerodynamic diameter of less than 2.5

micrometers) are especially important owing to their impact on human health, including respiratory diseases and disease of the heart and blood vessels (Zhang & Li, 2015). To obtain PM 2.5 variations, many studies are based on reports presented by pollution monitoring sites as the regional pollution measure, which certainly are not representative of the region (Brook et al., 2010). Therefore, Reanalysis Dataset resulting from satellite data provide the best spatial coverage for pollution studies.

Thus far, many studies have considered dust deposition. Although studies on deposition are not new, most of these studies in recent years have been conducted upon development of numerical models and satellite data. Despite the significant progress made in modeling and satellite monitoring, there is still no long-term study into dust deposition in Iran. Recent studies have investigated dust deposition using laboratory results for a short time and in a limited area.

Zender et al. (2003) studied the Mineral Dust Entrainment and Deposition (DEAD) model with a climatological approach (1990s) on the global scale and concluded that the dust transport from East Asia and Australia to some parts of the Pacific traveled a longer way as the particles were not larger than 3 mm. Cattle et al. (2005) assessed dust deposition in southeastern Australia under Aeolian processes to identify salinity and erosion effects, and found that a large part of these areas in Australia has a substantial dust input owing to high erosion and high salinity.

Osada et al. (2014) investigated the factors associated with temporal variations and spatial distribution in Japan, and they concluded that regardless of type of sediment, abundance of dust generally decreased with increased distance from the source region, demonstrating that selective removal of the larger particles occurred during the atmospheric transport. The study also showed that dust transport (more than 2 km) with a weak vertical gradient of the potential temperature carried dust particles into Japan and deposited them. Vincent et al. (2016) in their study investigated the variability of mineral dust deposition in the western Mediterranean region and southeastern France. The results of their research indicated that wet deposition was the main form for mineral dust deposit in the western Mediterranean region, while the contribution of the dry deposition (without rainfall at the surface) is negligible, accounting for approximately 10 to 46 percent of the main dust events depending on the sampling site. Provençal et al. (2017a) evaluated the PM 2.5 concentration using the MERRA Aerosol database in Israel and Taiwan. While confirming the accuracy of the MERRAero database, their research results showed that the PM 2.5 level was high owing to both vicinity of Israel to the Mediterranean Sea and sulfate particles produced by urban activities in Israel. The PM value of Taiwan is primarily composed of anthropogenic particles (sulfate, nitrate, and carbon) that are generated locally in China and is composed of mineral dust transport from the deserts in China and Mongolia. Provençal et al. (2017b) evaluated the MERRAero dataset for Europe in another study, and confirmed the results of this dataset and evaluated PM 2.5 regional variations.

A summary of the reviewed resources suggests that a significant progress has been made in the study of dust cycle (emission, transport, and deposition) over the last decade, which is owing to reproduction of satellites, ground-based dust observations, and development of numerical prediction models (Colarco et al., 2010). Most of the studies have focused on the inputs of global climate models, simulation of climatic systems, and complex interactions between its stimuli, including atmosphere, ocean, surface, and ice. Thus far, dust storms and atmospheric aerosols have been discussed in Iran more in terms of diffusion and transport. However, deposition and its related aspects have been discussed limitedly or ignored totally. Little attention is paid to: 1. Differentiation between wet deposition and dry deposition, 2. Urban dust pollution, 3. Spot measurement, and 4. Lack of a long-term climatic view of wet deposition and dry deposition processes. Therefore, the present study aims to assess wet deposition and dry deposition as the dust deposition load, and focuses on Fine Particles (PM 2.5) as a component for atmospheric pollution of Iran (with particular attention on important cities) on a seasonal basis, so that dust storms and the pollution caused by them in the context of Iran could be understood better.

2. Materials and Methods

2.1. Research area

The Islamic Republic of Iran (22 - 25°N; 43 -47°E) occupies a high plateau, bordered to the north by the Alborz Mountains and to the west by the Zagros Mountains; these ranges converge in the north west, with a greatest Height over 4000 m. A significant portion of dust emission comes from the Sistan Basin, on the eastern border with Afghanistan, at the western extent of the Dasht-e Margo desert. With a high geographical diversity, Iran has a total land area of more than 1,648,000 km^2, extending from 25° to 39° North latitude and from 44° to 63° East longitude. Its major deserts comprise of Dasht-e Kavir and Dasht-e Lut, which are located in the central and southeastern parts of the country. On the contrary, the two major mountain ranges of Alborz in the north and Zagros in the west significantly contribute to Iran's wide climate variation. The prevailing climate in Iran is classified as arid and semi-arid, except for the northern region, which is bordered on the Caspian Sea and has a very humid climate (Alijani & Harman, 1985). Fig. 1 depicts the topography of Iran and 0.50° × 0.625° geographic pixels for the MERRA-2 Database used in this study.

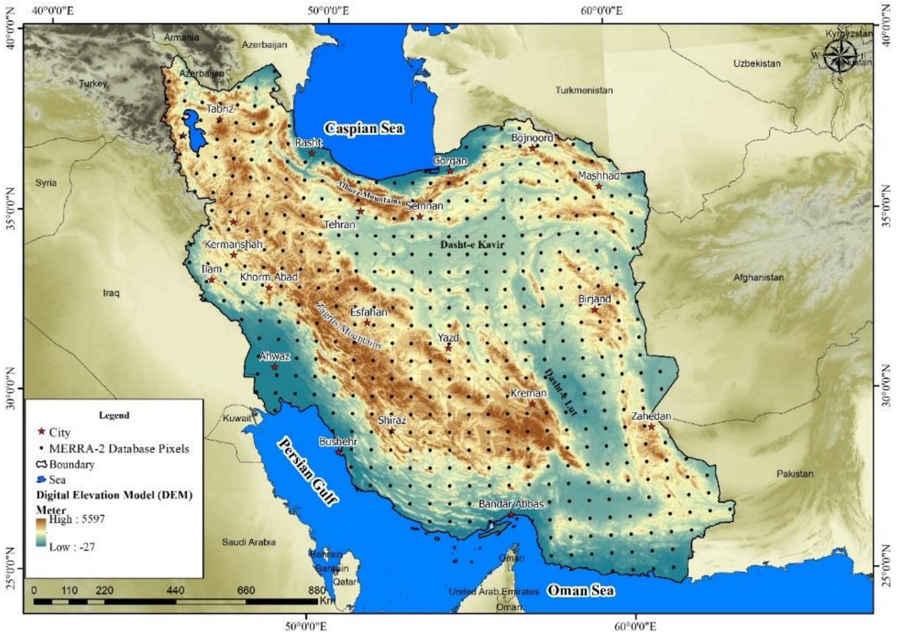

Figure 1: Topography of Iran and 0.50° × 0.625° geographic pixels for the MERRA-2 Database.

2.2 NASA’s Modern-Era Retrospective Analysis for Research and Application (MERRA)

In this study, NASA's MERRA database (version 2) was used to evaluate the Fine Particles (PM 2.5), dust wet deposition, and dust dry deposition.

MERRA stands for NASA’s Modern-Era Retrospective Analysis for Research and Application (Rienecker et al., 2011). It is a reanalysis dataset that builds on integrating satellite observations from the Earth Observing System, model data from the 5th version of the Goddard Earth Observing System (GEOS-5) atmospheric model, and data assimilation system (Rienecker et al., 2011; Molod et al., 2015). It aims to create a consistent database in both spatiotemporal of environmental, meteorology and climatology variables across the globe since the beginning of the satellite era. Lately in the newest version, bias-corrected aerosol optical depth observations from the MODIS on board the Terra and Aqua satellites and the Goddard Chemistry, Aerosol, Radiation and Transport (GOCART) model (Chin et al., 2002) are included in MERRA to produce a reanalysis of aerosols labelled “MERRAero”. GOCART simulates the sources, transport, sinks and concentration of sulfate (SO4), organic carbon, black carbon, sea salt, dust, and aerosols (Colarco et al., 2010). Dust and sea salt emissions are the result of surface properties and wind speed at the surface; moreover, their respective concentrations are classified in different diameter bins (Provençal et al., 2017a).

2.3. Fine Particles (PM 2.5)

Aerosols, depending on their size and chemistry, have different effects on horizontal vision and human health. Considering the importance of particulate matter (PM2.5) in air pollution and its impact on human health, this parameter is discussed more frequently than any other variable in the air pollution literature. The MERRAero simulation of aerosol chemistry is a significant progress for various air quality-related issues worldwide (Provençal et al., 2017a). It is because there are very few monitoring networks with such a differentiation between observations related to aerosols and dust. This is especially important for countries like Iran, which have unreliable observational data with inappropriate distribution.

PM 2.5 (PM with diameter ≤ 2.5 μm) of the MERRAero dataset is derived from hourly simulations of SO4, OC, BC, DS 2.5, and SS 2.5 parameters. From the existing equations evaluated by Chow et al. (2015), the Equation (1) was proposed:

$$PM = \text{Inorganic ions} + \text{Organic matter} + BC + DS + SS \quad (1)$$

GOCART simulates the sources, sinks, transport and concentration of sulfate (SO4), organic carbon (OC), black carbon (BC), dust (DS) and sea salt (SS) aerosols (Chin et al., 2002; Provençal et al., 2017a, b). DS and SS emissions are a function of surface properties and wind speed at the surface, and their respective concentrations are classified in different diameter bins.

Since MERRAero's ready-made data were employed in this study, further explanations on the relationship were avoided. Chow et al. (2015) and Provençal et al. (2017a, b) provided the full description of this relationship.

2.4. Validation of MERRA-2 database

Various parameters of MERRAero in different spheres of the globe, especially in developed countries, which have a strong observational network, have been evaluated, and the results have been confirmed. For example, PM 2.5 and its various chemical species are fully evaluated in the United States (Buchard et al., 2016), Europe (Provençal et al., 2017b), and Taiwan (Provençal et al., 2017a), whereby the results of the MERRAero dataset have been approved.

Before Evaluation MERRA-2 database in Iran, it was necessary to verify the data of MERRA-2 database. For this purpose, Root Mean Square Error (RMSE) (Equation 2), Coefficient of Determination (R2) (Equation 3) and Mean Bias Error (MBE) (Equation 4) methods were used. The mentioned methods are used in many studies to verify the modeling and have high performance.

$$RMSE=\sqrt{\frac{\sum_{i=1}^{n}(y_i-\hat{y})^{2}}{n}}, \qquad (2)$$

where n is the number of observational points, y_i is the simulated value for i^{th} point, and $\hat{y}$ is the observed value for i^{th} point.

$$R^2=\frac{\left[\sum_{i=1}^{n}(x_i-\bar{x})(Y_i-\bar{Y})\right]^2}{\sum_{i=1}^{n}(x_i-\bar{x})^2\sum_{i=1}^{n}(Y_i-\bar{Y})^2} \qquad (3)$$

$$MBE=\frac{\sum_{i=1}^{n}(x_i-Y_i)}{n} \qquad (4)$$

In Equations (1) and (2), X_i and Y_i are the real and simulated i^{th} data by the model, respectively; $\bar{X}$ and $\bar{Y}$ are the average of total data of X_i and Y_i in the statistical society, and n is the total number of samples evaluated (Osinowo et al., 2017).

2.5. Pearson correlation (PC) test

The Pearson correlation test evaluates the linear relationship between two continuous variables. A relationship between two variables is linear when a change in one variable correlates with a proportional change in the other variable. The test is widely used in statistics to measure the relationship between linear variables (Srivastava & Saran, 2017). This test is used to evaluate the relationship between wet and dry dust deposition and Fine Particles (PM 2.5) from the MERRA-2 Database and geographic features. The Pearson correlation coefficient is used to measure the strength of a linear association between two variables, where the value r = 1 means a perfect positive correlation and the value r = -1 means a perfect negative correlation (Equation 5).

$$r=\frac{\sum_i(x_i-\overline{x})(y_i-\overline{y})}{\sqrt{\sum_i(x_i-\overline{x})^2}\sqrt{\sum_i(y_i-\overline{y})^2}} \qquad (5)$$

2.6. Linear regression method

Linear regression method was used to evaluate the wet and dry and PM 2.5 value obtained from the MERRA-2 Database with height, latitude, and longitude (Equation 6).

$$wet\ and\ dry\ and\ PM\ 2.5 = m \times Geographical\ Components + c \qquad (6)$$

where c is the intercept; m is the slope (Ahmadi et al., 2018). Wet and dry and PM 2.5 illustrate wet and dry dust deposition and Fine Particles (PM 2.5) from the MERRA-2 Database, respectively. R^2 is defined as the coefficient of determination or square of correlation coefficient representing the correlation between wet and dry dust deposition and Fine Particles (PM 2.5) from the MERRA-2 Database and meteorological Geographical Components.

3. Results and Discussion

3.1 MERRA-2 database validation

As discussed in the methods section, PM 2.5 Obtained Ground stations (the last five years; 2013-2016) was used in this study to validate the MERRA-2 database. Validation results are displayed in Table 1. The correlation coefficient (R2) for Tehran, Tabriz, Mashhad, Isfahan and Ahvaz were 0.856, 0.874, 0.897, 0.798 and 0.845, respectively. The

Root Mean Square Error (RMSE) and Mean Bias Error (MBE) values.

Table 1: MERRA-2 Database PM 2.5 validation with selected data stations

City	RMSE	MBE	R^2
Tehran	5.845	1.254	0.856
Tabriz	4.658	1.325	0.874
Mashhad	4.325	1.985	0.897
Isfahan	5.478	1.254	0.798
Ahvaz	5.102	1.658	0.845

Confirmed the high accuracy of the PM results of MERRA-2 database in Iran. This evaluation supports the assumption that MERRAero performs well in simulating the concentration of dust originating from regional sources throughout the year

3.2. Fine Particles (PM 2.5), wet and dry deposition variability and its relation to the Geographical Components

The statistical data of Fine Particles (PM 2.5), dust wet deposition, and dust dry deposition of Iran are presented on a seasonal basis using the data of the MERRA-2 dataset in Figures 1 to 3. In addition, to better study the seasonal variation of Iran's wet and dry dust deposition, all months of the year are presented using the Stacked Column chart (Fig. 5), so that seasonal deposition amounts can be better discussed. As the table shows, for the dry deposition, the maximum mean and median values are those of the spring and summer. On the contrary, the winter and spring have the highest values of wet deposition. The range of changes also increases naturally in the seasons with the maximum mean value, where the range of variations is maximal in the summer for dry deposition, and in winter for wet deposition. Skewness and kurtosis indicating the degree of asymmetry and heavy-tailedness of the potential distribution, respectively, are positive in both wet and dry deposition variables.

As it can be seen, the data are not distributed symmetrically, since skewness is not zero in any of the parameters. The first quartile can be Considered areas with wet/dry deposition or low pollution, and the third quartile is associated with wet/dry deposition or high pollution deposition areas. Accordingly, for example, in winter and spring, a quarter of Iran undergoes wet deposition of more than 0.314 µg m^{-2} and 0.312 µg m^{-2}. Alternatively, concerning dry deposition, it can be stated that in the summer, 75% of the country has dry deposition of less than 0.080 µg m^{-2}. In the last section of Table 2, the statistical data of PM 2.5 are presented. As expected, due to dust events, the summer has the maximum mean Fine Particles (PM 2.5) in Iran (29.99 µg m^{-2}), followed by the spring, fall, and winter. Skewness and kurtosis also provide behaviors similar to those of the previous two parameters.

Maximum values and range of change in the summer and spring have the maximum value compared to other seasons. With the average value of 16.48 (µg m^{-2}) PM 2.5, the winter has the lowest value in the country owing to rain events. The amount of PM 2.5 and particle size can be considered factors contributing to regional understanding of dust, so that finer particles are associated with anthropogenic and coarser particles with natural factors, where the latter is related to the large desert and arid areas located in the southwest, south, and southeast of Iran. Seasonal variations in PM 2.5 levels in Iran are due to the synergistic effects of variations in emissions and seasonal atmospheric conditions (mixture of upper layers of the atmosphere, reiteration of the air inversion phenomenon). During the cold period of the year, when the dust

Table 2: Statistical characteristics of wet and dry dust deposition and Fine Particles (PM 2.5) in Iran (1980-2016)

Summary Statistics									Season	Variable
Kurtosis	Skewness	Standard deviation	Mean	3st Quartile	1st Quartile	Range	Maximum	Minimum		
9.093	2.592	0.022	0.041	0.046	0.028	0.180	0.193	0.013	Winter	Dust Dry Deposition
4.765	1.814	0.023	0.089	0.097	0.073	0.156	0.208	0.052	Spring	
6.207	2.125	0.028	0.072	0.080	0.056	0.194	0.228	0.034	Summer	
7.019	2.374	0.019	0.043	0.046	0.031	0.139	0.157	0.019	Autumn	
7.364	2.514	0.305	0.267	0.314	0.084	2.015	2.054	0.039	Winter	Dust Wet Deposition
6.872	2.328	0.214	0.252	0.312	0.112	1.480	1.541	0.061	Spring	
19.37	3.839	0.053	0.038	0.041	0.009	0.474	0.476	0.002	Summer	
16.66	3.648	0.140	0.089	0.100	0.017	1.073	1.079	0.006	Autumn	
4.993	2.054	7.782	16.480	18.694	11.272	51.010	57.671	6.661	Winter	Fine Particles (PM 2.5)
4.120	1.841	9.420	27.042	30.140	21.214	60.823	72.739	11.916	Spring	
6.260	2.132	14.219	29.998	35.180	20.638	98.427	109.22	10.797	Summer	
4.582	1.905	8.372	20.221	23.771	14.404	52.647	60.719	8.072	Autumn	

definitely affects Iran less significantly, PM 2.5 value is also lower. However, the fall showed higher PM 2.5 values, which can be attributed to increased emissions due to atmospheric pressure differences, the start of fossil fuel consumption, and biomass burning.

Table 3 presents the seasonal wet and dry dust deposition and PM 2.5 correlation in Iran with height, latitude and longitude characteristics. Clearly, the maximum correlation in the three variables of Iran belongs to height, followed by latitude and longitude; meanwhile height and latitude are strongly and reversely correlated with each other (that is significant at 0.05 level). The maximum Fine Particles (PM 2.5) correlation with Heights occurs in the fall, spring, winter, and summer, respectively. In the spring (MAM: March, April and May), the Fine Particles (PM 2.5) show a correlation with latitude with the amount of -0.595. the linear regression method is also used to evaluate the relationship between the wet and dry deposition as well as PM 2.5 value and the geographic components. The value of R2 obtained for three variables was owing to the importance of the similar relationship of the correlation (Pearson) value. Linear regression results have again demonstrated the important role of Heights in the PM 2.5 value of Iran, and then latitude plays the role of an important factor. The most important reason for increasing the correlation of R2 value of latitude and height with PM 2.5 concentration in Iran is the presence of different mountain ranges with their special orientations. The Zagros Mountains, which can play a significant role in the spatiotemporal variations of wet and dry dust deposition and PM 2.5 in Iran, are a barrier to the transfer of western aerosols to central Iran with their northwest-southeast expansion, which is one of the main reasons for increasing the concentration of aerosols in the western and southwestern regions of Iran.

Table 3: Correlation (Pearson), linear regression and P-values of wet and dry dust deposition and PM 2.5 concentration with geographical components in Iran.

P-values			Linear regression Coefficients of determination (R²)			Correlation (Pearson)			Season	Variable
Height	Latitude	Longitude	Height	Latitude	Longitude	Height	Latitude	Longitude		
< 0.0001	**< 0.0001**	0.943	0.112	0.149	0.000	**-0.335**	**-0.386**	-0.003	DJF	Dust Dry Deposition
< 0.0001	0.434	**0.000**	0.041	0.001	0.071	**-0.202**	-0.035	**-0.266**	MAM	
< 0.0001	**0.036**	**0.000**	0.086	0.009	0.045	**-0.293**	**-0.094**	**-0.213**	JJA	
< 0.0001	0.866	**0.001**	0.085	0.000	0.020	**-0.291**	0.008	**-0.143**	SON	
0.233	0.168	**0.000**	0.003	0.004	0.194	0.054	-0.062	**-0.440**	DJF	Dust Wet Deposition
0.000	**< 0.0001**	**0.000**	0.027	0.107	0.357	**0.165**	**0.327**	**-0.547**	MAM	
0.925	**< 0.0001**	**0.000**	0.000	0.056	0.033	-0.004	**0.237**	**-0.183**	JJA	
0.016	**< 0.0001**	**0.000**	0.012	0.192	0.225	**0.107**	**0.438**	**-0.474**	SON	
< 0.0001	**< 0.0001**	**0.000**	0.169	0.247	0.029	**-0.411**	**-0.497**	**0.170**	DJF	PM 2.5
< 0.0001	**< 0.0001**	**0.000**	0.183	0.354	0.063	**-0.428**	**-0.595**	**0.251**	MAM	
< 0.0001	**< 0.0001**	**0.000**	0.157	0.222	0.053	**-0.396**	**-0.471**	**0.231**	JJA	
< 0.0001	**< 0.0001**	**0.000**	0.185	0.125	0.063	**-0.431**	**-0.353**	**0.251**	SON	

Values in bold are different from 0 with a significance level alpha=0.05
(DJF: December, January, and February; MAM: March, April and May; JJA: June, July and August; SON: September, October and November)

3.3. Spatial-temporal distribution of dry dust deposition

Figure 2 displays the seasonal values of dry deposition in Iran. For Iran, several important dust regions can be noted, having a high rate of deposition and pollution. As the figure clearly shows, in all seasons, the southwest, the Persian Gulf coast in the Bushehr province, the coast of the Oman Sea in the southeast, and eastern regions of Iran have the highest rate of dry deposition in Iran. The first region, having high levels in all seasons, is the southwest and province of Khuzestan with the highest dry dust deposition amount, so that the obtained values were 0.193 µg m^{-2} in the winter (Fig. 2-A), 0.208 µg m^{-2} in the spring (Fig. 2-B), 0.228 µg m^{-2} in the summer (Fig. 2-C), and 0.157 µg m^{-2} in the fall (Fig. 2-D). Owing to its proximity to the great deserts of Iraq and Saudi Arabia, the southwest of Iran has the maximum dry deposition, which can be described as a major deposition in Iran. The second region includes Dasht-e Kavir extending from the center of Iran to the Afghanistan border. Dasht-e Lut in southeastern Iran, the Sistan basin in eastern Iran, Dasht-e Khash in western Afghanistan, and the deserts of Kharan and Makran in southeastern Pakistan are mainly active in the summer (Fig. 2-C) and create a very high concentration of dust that even reaches the Arabian Sea.

These areas are located in arid and salty lands having rivers, seasonal lakes, or dry beds, which drain soft mountain sediments to these areas. For example, Dasht-e Kavir is fed by the Alborz mountain range, Makran plain by Makran sediments, and Sistan plain by Hindukush mountain range sediments (Alizadeh-Choobari et al., 2014). Among the sources of dust, the Sistan Basin has been considered the most active source in West Asia since 1999 (Rashki et al., 2012). The third zone begins from the deserts of Thar and Rann of Kutch in the northwest of India to the proximity of the Pakistan border. The

Thar Desert is confined by the Ladakh in the north to the vast Indus alluvial plain in the west, the Rann of Kutch in the south and the Aravalli hills in the east. Most of these areas are characterized by large sand dunes that constantly receive sediments.

The sources of these deposits include dried lake basins, alluvial deposits, and Aeolian processes left from the late Pleistocene and the coastline of the Arabian Sea, which stand as the main source of dust emissions from the mid-spring to the summer (May to August). Rashki et al. (2012), in the study of dust deposits and air quality in the Sistan region, stated that large and heavy particles traveled in the vicinity of the Earth, while small particles rose at high heights and traveled longer distances. Thus, the amount of dust carried depends first on the severity and duration of the travel, and second, on the wind speed and distance from the source of dust.

The most important factor leading to lower deposition rates in the central regions of Iran than the border areas of the southeast to the southwest of Iran is the height. The Zagros Mountains, stretching from the northwest to the southeast, stand as a barrier to the transport of western dust to central Iran, and this is a major reason for increased deposition of dust in the west and southwest of Iran. Figure 2 shows the deposition variations and their percentage. In all the studied stations except for Chabahar (Fig. 5-c), where the dry deposition value is maximal in all seasons, wet deposition is dominant in other seasons. Ilam (Fig. 5-B), Rasht (Fig. 5-D), Kermanshah (Fig. 4-F), and Gorgan (Fig. 5-G) have the lowest dry deposition in the winter. With the onset of the spring, dry deposition replaces wet deposition, so that in Ahvaz in April, dry deposition accounts for approximately 50% of the total deposition, while at the end of the spring season in June, this amount is above 95%. These increasing conditions are observable in all stations except for Chabahar (Fig. 5-C). Interestingly, Chabahar has a drop in this regard, where dry deposition equals 75% in April, 60% in May, and 46% in June. This is owing to increased humidity in May and June. Therefore, it can be concluded that with increasing precipitation and relative humidity, there is a greater chance for adhesion of the particles in dust production regions, leading to reduced production of dust in the source area, and finally resulting in reduced deposition in the target area. Furthermore, precipitation affects soil moisture and vegetation cover as two important factors controlling dust, thereby reducing the amount of dust production.

An interesting point for this region of Iran (southeast represented by Chabahar) is the decline in dry deposition during the warm period of the year, so that after August, the dry deposition trend begins to rise, reaching 90% in November. In Rasht (Fig. 5-D), the dry deposition does not exceed 35% in any month, which is expectable due to its weather conditions. Focusing on the south of the United States, Reheis and Urban (2011) concluded that the rate of dust deposition decreased with increasing relative humidity, being consistent with the results obtained in Iran. According to Arkian and Nicholson (2018), air masses arriving in Iran from Europe and the Mediterranean Sea in the winter bring substantial precipitation for Iran, reducing dry deposition in favor of increased wet deposition. The relatively higher rate of atmospheric dust in the summer in relation to other seasons can be attributed to factors such as soil dryness (lack of water in wetlands such as Hamoon and Houralazim) and the lack of vegetation on the ground, including factors affecting the transfer of more quantities. In the summer and fall, the reason for increased deposition on the Caspian Sea coastline is primarily sea salt followed by dust from Turkmenistan's deserts.

Sistan is one of the most active sources of dust storms in Asia, so that dust storms occur almost all through the year. However, dust storms occur maximally during the summer and spring, and the climatic parameters contributing to dust storms include wind speed and direction, drought, and high temperatures. When no rain is recorded, dust deposition is principally guided by dry sediment processes (Vincent et al., 2016). Particle deposition in Iran is more controlled by dust events. Löye-Pilot and Martin (1996) also argued that significant deposition occurred in dry conditions; for example, in cases of limited or short rain events or days with no fog in the atmosphere, rainfall cannot be properly identified, since precipitation is usually evaluated classically.

Singer et al. (2003) also argued that the size of deposited dust particles reflected three factors: 1. Distribution of the size of the dusts from the source region; 2. Distance from the source; 3. Frequency and time of precipitation, which are consistent with the obtained results in this study.

3.4. Spatial-temporal distribution of wet dust deposition

Figure 3 illustrates the seasonal temporal-spatial variations of wet deposition in Iran. As the figure shows, wet deposition changes in Iran are closely associated with the climatic conditions and influential climate systems in the country. In the winter (Fig. 3-A) and spring (Fig. 3-B), the maximum wet deposition is found in the Zagros region, particularly in the middle Zagros. The maximum wetland deposition is in the winter 2.05 (µg m^{-3})

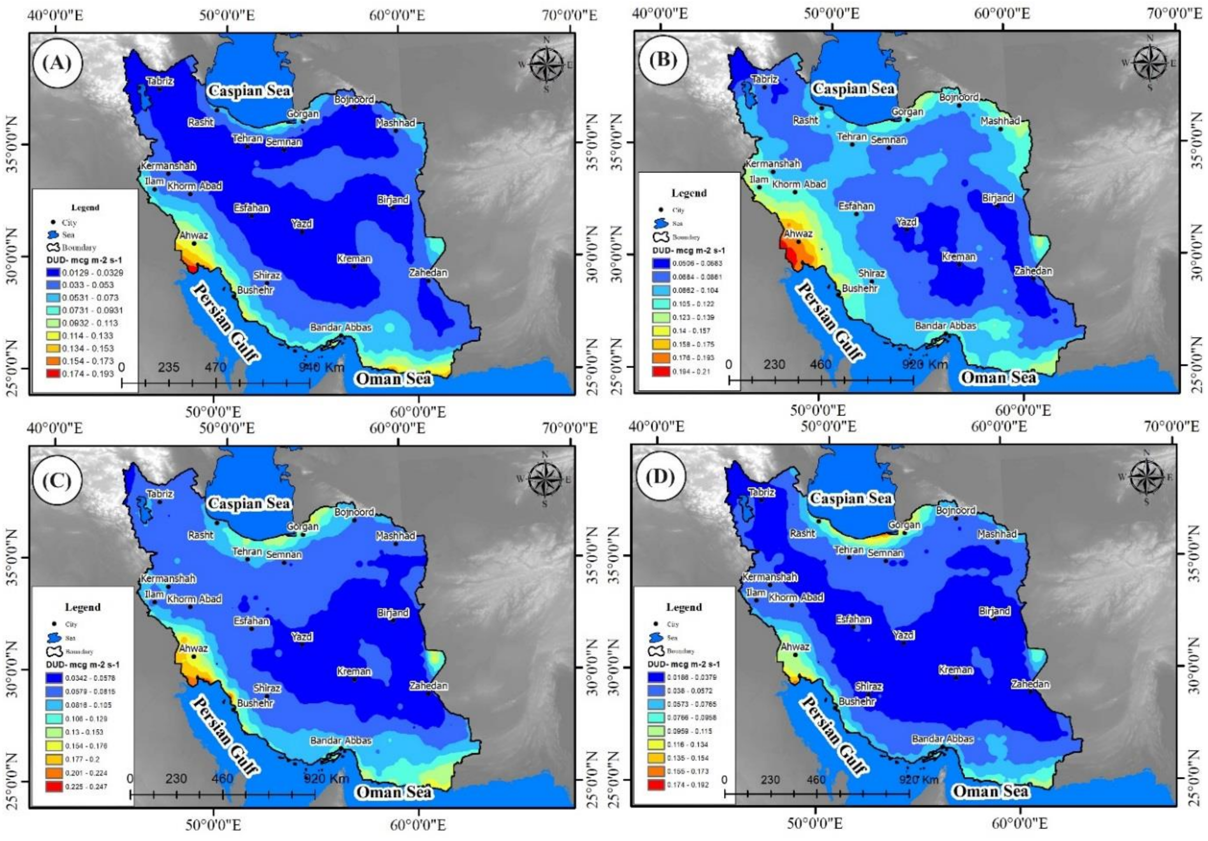

Figure 2: Seasonal Dust dry deposition in Iran; A-Winter; B- Spring; C- Summer; D- Fall (1980-2016).

and in the spring 1.54 (μg m^{-3}). Regarding precipitation in Iran, Alijani, (1979) has stated that Middle Eastern cyclones are produced in the four centers of the Adriatic Sea, the Greek Sea, the island of Cyprus, and the southeast of the Zagros Mountain Range. Compared to the results obtained for wet deposition in the winter and spring, it is clear that in the winter, the south-eastern region of the Zagros experiences the maximum wet deposition, demonstrating the important role of precipitation in wet deposition. Building on their finding concerning the inverse relation between rainfall and the rate of dust deposition, Ta et al. (2004) concluded that at a given wind speed, the transported dust load rate reduced as perspiration increased. Therefore, despite their high speed, the prevailing western winds do not carry dust particles, given their source of production. Moreover, as they blow during cold seasons of the year, they mainly lead to precipitation and increase relative humidity, leading to a decreased rate of dust deposition in the affected areas.

This result is very clear for Iran in the summer (Fig. 3-C). During this season, the Azores subtropical high pressure affects Iran toward the Alborz Mountains (Alijani, 1979; Ghalhari et al., 2016). Humidity advection becomes more important in northern Iran along with the strengthening and propagation of the Siberian high in the fall. It reaches its peak in December and makes the nucleus of Iran's annual rainfall in the southwest of the Caspian Sea near the Anzali Port.

Alongside with changes in the rainfall patterns of Iran, wet deposition is also transported. In the summer (Fig. 3-C), there is no wet deposition across Iran except for the southeastern coastline that is affected by the Monsoon precipitation system and the highly humid coasts of the Oman Sea and the Persian Gulf (toward the coasts of Bushehr). In the fall (Fig. 3-D), as mentioned above, owing to the Siberian high, the maximum wet dust

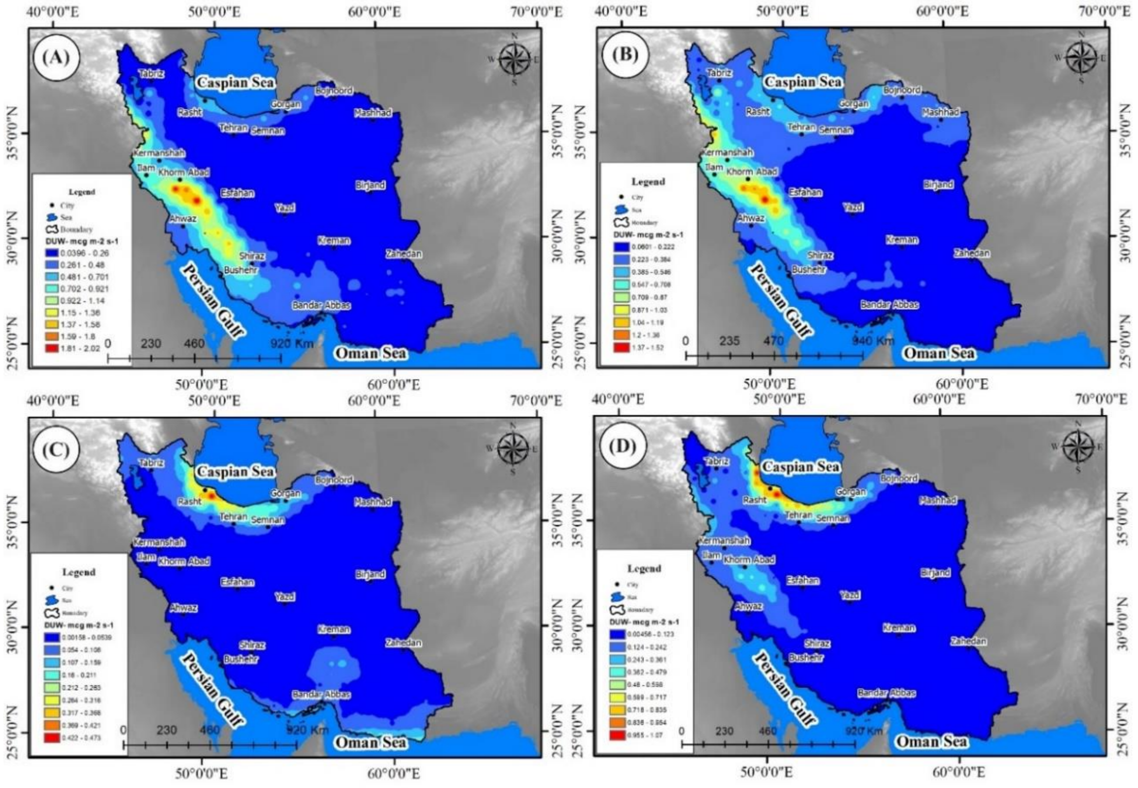

Figure 2: Seasonal dust wet deposition of Iran; A-Winter; B- Spring; C- Summer; D- Fall (1980-2016).

deposition occurs on the coastline of the Caspian Sea. In Kuwait, Al-Harbi (2015) found that the months with many dust-containing winds had the highest rate of dust deposition (Fig. 2, dry deposition). Kaskaoutis et al. (2016) also stated that wind speed and air temperature were positively associated with dust deposition rate where the dust deposition rate increased as the wind speed and air temperature increased (Fig. C-1 and Table 2).

Klingmüller et al. (2016) indicated that Iran's Aerosol Optical Depth (AOD) was considerably influenced by precipitation. This suggests the important role of the transport routes of aerosols travelling into Iran passing through routes with significant rainfall like the Zagros mountain range, confirming the results of the present study. Seasonal variations in wet and dry deposition in Iran have shown that the amount of dust deposition in areas with low heights is much faster than those located at higher heights. Hojati et al. (2012) also reported this finding in their laboratory studies of dust deposition in Isfahan. In similar lines, Wang et al. (2015) reported the highest deposition rate during the spring in the southwestern and northeast parts of Beijing city center, stating that the mountains in the north-west of the city had the least amount of dust deposition on the surface.

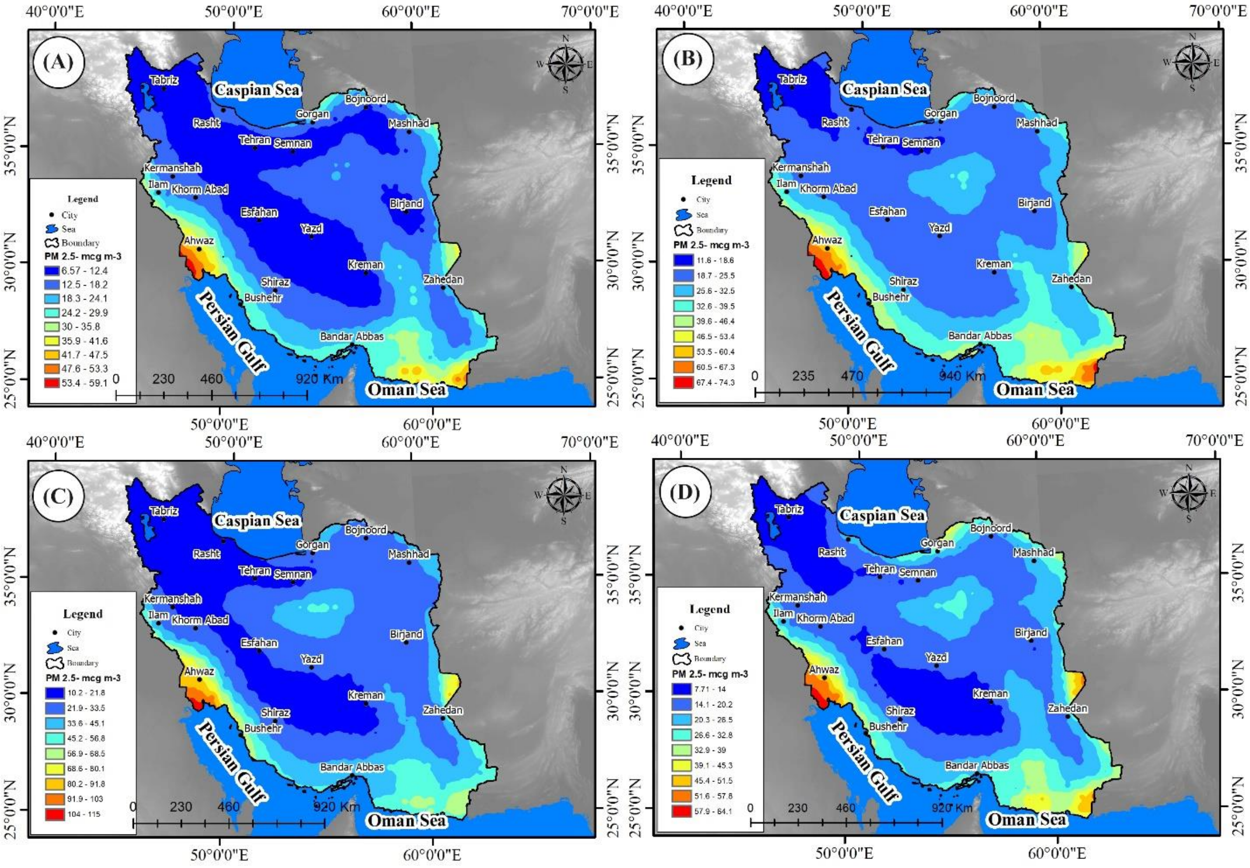

Figure 4: Seasonal Fine Particles (PM 2.5) in Iran; A-Winter; B- Spring; C- Summer; D- Fall (1980-2016).

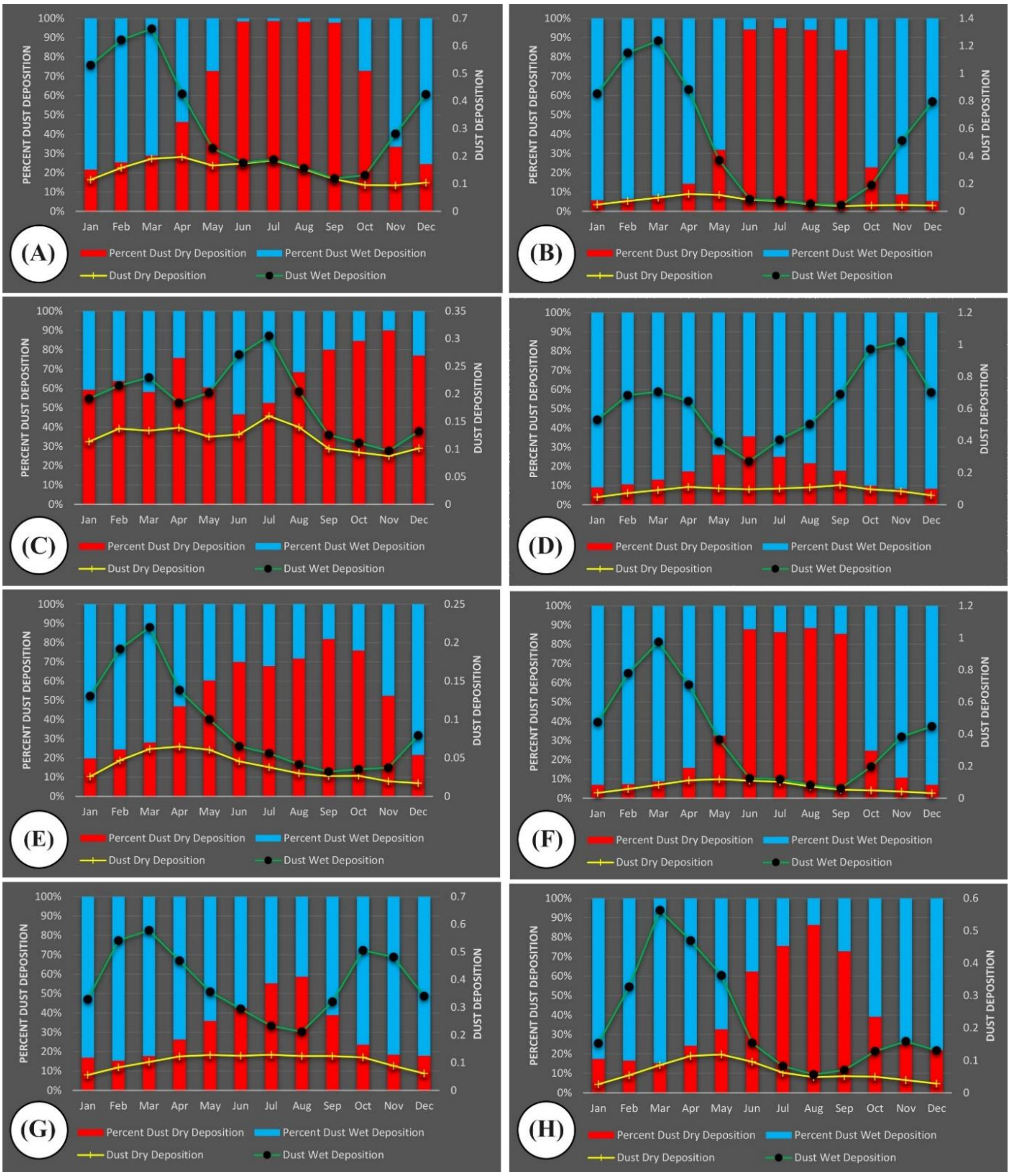

Figure 4: Percentage of wet and dry deposition variations in Iran along with internal variations. A- Ahwaz; B- Ilam; C- Chabahar; D- Rasht; E- Zahedan; F- Kermanshah; G- Gorgan; H- Mashhad.

The summary of the results concerning the dry and wet deposition rates has that the temporal and spatial variations of dust deposition is largely associated with climatic characteristics of the region. The correspondence between the model of atmospheric impact systems and the dust deposition rate in Iran can strengthen the hypothesis that the most important sources of Iran's dust production are in the west, southwest, and southeast parts of Iran.

3.5. Spatial-temporal distribution of Fine Particles (PM 2.5)

Figure 4 shows the long-term seasonal value of Fine Particles (PM 2.5) in Iran. In line with the amount of dust entering the country and the amount deposited in areas known as dust hotspots, the amount of Fine Particles (PM 2.5) will also be naturally maximal. Alongside this, the southwest of Iran, the coastlines of Bushehr, and southeast and east of Iran have shown the maximum amount of PM 2.5. The maximum amount of PM 2.5 in all seasons belongs to southwest of Iran, so that the values were 57.67 µg m^{-3} in the winter, 72.73 µg m^{-3} in the spring, 109.22 µg m^{-3} in the summer, and 60.71 µg m^{-3} in the fall.

Iran is located in western Asia, surrounded by arid and semi-arid deserts. Its PM concentration load is relatively high and is primarily composed of minerals caused by dust storms.

Accordingly, since the amount of soluble salts in the Zagros area is negligible, it seems that the source of dust lies in farther regions in the western provinces of Iran or neighboring countries like Iraq. Earlier research (Al-Juboury, 2009) reported the concentration of saline and/or gypsiferous soils in central and southern Iraq.

4. Conclusion

This article evaluates the concentrations of particulate matter (PM) and wet and dry deposition simulated at the surface by Version 2 of the Aerosol Reanalysis of NASA's Modern-Era Retrospective Analysis for Research and Application (MERRAero) over Iran.

The results showed the MERRAero performs well in simulating the concentration of dust originating from regional sources throughout the year. Winter and spring have the highest values of wet deposition. The range of changes also increases naturally in the seasons with the maximum mean value, where the range of variations is maximal in the summer for dry deposition, and in winter for wet deposition. Seasonal variations in PM 2.5 levels in Iran are due to the synergistic effects of variations in emissions and seasonal atmospheric conditions (mixture of upper layers of the atmosphere, reiteration of the air inversion phenomenon).

The results of this study into the dust deposition rate in Iran indicated that the rate depends entirely on the rapid supply of dust from the source, precipitation, and atmospheric volatility, and when it comes to a specified region, the rate is mainly dependent upon climatic conditions in the source area and the deposition area. Moreover, the rate of dust deposition increases along with increased frequency of spring and summer storms and decreases with increasing humidity in the winter. In Zagros and Alborz highlands, dust deposition decreases as the Height increases.

The simulations of this base for PM 2.5 concentration have shown that Iran has relatively high levels of PM concentration with different compositions compared to other parts of the world such as the United States (Buchard et al., 2016), Europe (Provençal et al., 2017b), and Taiwan (Provençal et al., 2017a). The high levels of PM 2.5 in Iran are primarily owing to natural particles (mineral dust and sea salt), and secondarily, owing to anthropogenic activities. Since a significant portion of Iran's PM 2.5 is from mineral dust, it can be acknowledged that MERRAero works well in simulation of dust with local and regional origins.

The study clearly showed that both dry and wet depositions varied between the sites and season, suggesting the significant impact of industrial activities in modifying the atmospheric input.

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