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Seasonal Variation of Sulphate Aerosols and its Optical Properties Over Karachi During 2018

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Abstract. Seasonal variation of sulphate aerosols along with its optical properties and its dependence upon meteorological parameters are studied over Karachi, Pakistan during 2018 by using Giovanni data, where MEERA-2 analysis has been performed using OpenGrADS. Analysis of results showed that mass concentration (5-13 μg/m^3) and column density (19-24.5 mg/m^2) of sulphate aerosol and its extinction factor (0.18) is high in winter and autumn seasons showing dependence on biomass burning and fossil fuel combustion in the industrial sector. Low precipitation and wind speed favour the accumulation of pollutants and their transport from Nawabshah and Hyderabad to Karachi. On the other hand, in summer and spring low biomass burning, small retention time due to frequent precipitation, causing washing of air and reversal of wind direction are all the factors preventing the accumulation of pollutants in the area. This cause a decrease in the mass concentration (1.9-3 μg/m^3), density (9.8-13 mg/m^2) and extinction factor (0.06) of sulphate aerosols in the troposphere.

Keywords: MEERA-2, aerosol optical depth, mass concentration, density mass column, giovanni

Introduction

The increase in migration of the global population to urban areas has increased environmental issues and exerted an extensive load of pollutants on environments (Hashmi *et al*., 2005; Duncan *et al*., 2003). The air quality in Karachi is heavily degraded by vehicular smoke, especially Buses and Rickshaws, house fires, burning garbage in open areas and industrial emissions but the environmental organizations and government seem to give no attention to dealing with this issue timely Hashmi *et al*. (2018). Automobiles operating on liquefied petroleum and compressed natural gas release major air polluters and degrade 70 to 75% of air quality in Karachi Hashmi *et al*. (2017). Change in weather and visibility is also affected by air pollution. Humidity and temperatures are also affected by increased average values of coarse (161 μg/m^3) and fine (81.8 μg/m^3) particles in the air. Sulphate particles are attached with $PM_{2.5}$, therefore they have same health effects arise from $PM_{2.5}$ exposures Nafees *et al*. (2012). The sulphate ion is a polyatomic anion with the empirical formula $(SO_4)^{2-}$. Sulphates release from combustion of biomass and fossil fuels appear as aerosols (microscopic particles) in air Ali *et al*. (2014). One kilogram of fossil fuel and biomass burning release approximately 0.02 Kg of SO_2 in air Perera (2017). In the atmosphere, sulphates react with water droplets and form acid rain due to their acidic properties Khokhar *et al*. (2016). Main effect of sulphate is the dispersion of light which increases the Earth's albedo and affects climatic conditions Yasmeen (2011). This effect of increased earth albedo causes the cooling effect of negative radiative forcing (0.4 w/m^2) compensating the effect of 2.4 w/m^3 caused by green house gases. To combat the warming of green house gases, scientists are inspired by the potential of geo engineering schemes in which sulphur could be continuously injected artificially into stratosphere. But some recent past studies like volcanic eruption, hydrological cycles etc. are also come in discussion which are caused by sulphate aerosol when it is injected in stratosphere, causing droughts in arid regions (Takemura, 2020; Itahashi *et al*., 2019). Absorption of infrared radiation by sulphate aerosol in stratosphere is also a point of concern which at the end transform stratosphere circulations. Sulphate aerosol also effects ozone by causing chemical reaction in stratospheric polar clouds which alter atmospheric chemistry and depleting its cycles Brodowsky *et al*. (2021). Sulphate

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aerosols perform function of cloud condensation nuclei which create smaller droplets of water in large quantity. These droplets diffuse light more effectively as compared to their counterpart and the process is named as Twomey effect (Khokhar *et al*., 2016; Chughtai *et al*., 2014). These small droplets of aerosols cause further knock-on effects of cloud condensation nuclei by increasing height of clouds which facilitate the cloud formation even at low humidity, suppress drizzle and increase life span of clouds Randles *et al*. (2017). Sulphates can also change particle size distribution which affects radiative properties of clouds in a process that is not fully understood. Chemical effects of sulphate include changing in accommodation coefficient and mixing of slightly soluble substances and soluble gases like formation of acid rain (Khan *et al*., 2017; Kazi, 2014). Sulphate also cause an atmospheric cooling effect of up to 2 w/m^2, therefore involved in global dimming process Javid *et al*. (2018). Sulphate also contributes in formation of stratospheric aerosol. Oxidation of sulphur dioxide injects stratospheric aerosol which cause cooling effect during 1-2 years of life span in stratospheric and effect climatic conditions (Tariq and Haq, 2018; Ali *et al*., 2014). Health effects comprise reduction of lungs function, irritation in breathing which can enhance risk of hospitalizations especially in emergency department and can cause death in such people who already have issues of lung or chronic heart diseases (Khjawa *et al*., 2012; Jacob and Winner, 2009). Sulphates are usually effective in reducing visibility by scattering light. This light scattering decreases visual clearness and degrades colours Ahmad *et al*. (2014). Acid rain can also affect tree needles and leaves which decrease their photosynthesis capacity. Metals, buildings, stone and paint undergo acid damage due to dry deposition of acidic sulphates Randles *et al*. (2017). The objective of the research is to analyze the concentration of sulphate in ambient air of Karachi by using spatial data and atmospheric dispersion modeling technique, analysis of sulphate optical properties to access air quality in Karachi and analysis of correlation between meteorological factor and sulphate concentration in ambient air.

Study area. A mega city and provincial capital of Sindh, Karachi is the most populous city in Pakistan shows in Fig. 1. It ranked fifth among most populated cities of the world. This city has Pakistan most financial and leading industrial center. It is philanthropic, educational political, economic and cultural hub as well as most multicultural city of Pakistan. Karachi consists of two biggest seaports (Port Bin Qasim and Port of Karachi) on Arabian sea which provide transport platform for Pakistan described by Khan and Sarwar (2014). Karachi has prolonged summer season which makes conditions of arid climate but temperature of the city is dwindled by oceanic effect of Arabian sea. Annual average precipitation level in Karachi is very low because of less rainfall which occurs mostly during month of July and August of monsoon season. Summer season is very humid and hot which cause episode of heat wave in the city. Cold air from sea and monsoon rainfalls moderate the temperature in summer season. Climate of winter season is very dry and occurs between months of December to February. This city is near to sea which makes a near-constant humidity level around the year.

Materials and Method

Data extraction. Monthly data of all meteorological parameters including temperature, pressure, precipitation, relative humidity, wind speed along with sulphate mass concentration, column density and aerosol optical properties for Pakistan was extracted from Giovanni in the form of NetCDF format (file format which store multidimensional scientific data). Time averaged map was generated by selecting date range from January to December, 2018. Data source of MEERA-2 Model was used for data extraction. (MERRA-2) provides data at 0.5 × 0.625 resolution from time period of 1 January

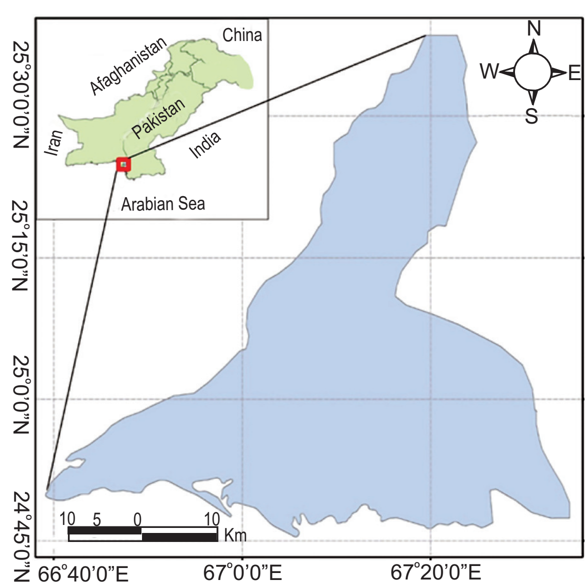

Fig. 1. Associations of the study area.

1980 to the present date. MERRA-2 is created using the data assimilation system version 5.12.4 and Goddard Earth Observing System, version 5 (GEOS-5) atmospheric model. MERRA-2 provide data about change in anthropogenic elements of aerosols and their relationship with climate and distribution. It collects data from 250 m to 1 Km pixel size on a 0.5° × 0.66° grid with 72 layers. Most of the data of aerosol optical depth (AOD) present in MEERA-2 is provided from Moderate Resolution Imaging Spectroradiometer (MODIS) sensors present on Aqua and Terra spacecraft's Rienecker *et al.* (2011). In order to generate maps, NetCDF files were run on OpenGrADS software. The Grid Analysis and Display System (GrADS) is a cooperative desktop tool for easy access, exploitation and creation of images from data of earth science. The OpenGrADS Project seeks to create advanced boundaries and expansions based on the main GrADS engine. The power of GrADS come from its availability, speed and ease of use on a large number of platforms. After that annual data of all the meteorological parameters were generated for Karachi city in CSV (comma-separated values file) format, which save data in tabular format.

Results and Discussion

Meteorological maps of Pakistan have provided a detail insight into various aspects that has been described as under observed in June and lowest value of <-10 °C is observed in December. High temperature in June is due to summer season in which earth is farthest to sun in its orbit and receive sun rays at steeper angle from sun. The amount of light reaching at a point increased because sun rays do not spread so much and more energy particles hit at a particular surface. Also, daytime is long which increase the time of exposure of earth surface to sun rays and temperature increases. In December sun rays reach earth surface at low angle causing a reduction in the solar at the surface. Also, less daytime decreases the exposure time of earth surface to heat energy and temperature decreases.

Atmospheric pressure. Figure 3 shows annual level of atmospheric pressure in Pakistan during 2018. Maximum atmospheric pressure value of 1000-1050 hPa is observed in December and lowest concentration from 500-600 hPa is observed in July. Value of pressure started to be decreased from month of February to minimum in month of July at 989 hPa. After that, its vales increased with maximum value observed in December at 1008 hPa. In summer and spring season (from March to August), temperature in Karachi is usually high (Fig. 2), that ultimately warm the air. This warm air rise creating low air density and atmospheric pressure decrease Javid *et al.* (2018). However, in winter and autumn season (from September to January),

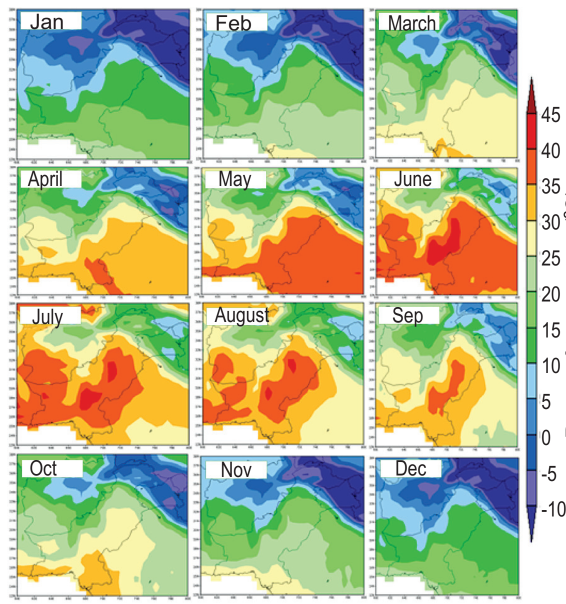

Fig. 2. Variation in temperature of air (°C) over Pakistan during 2018.

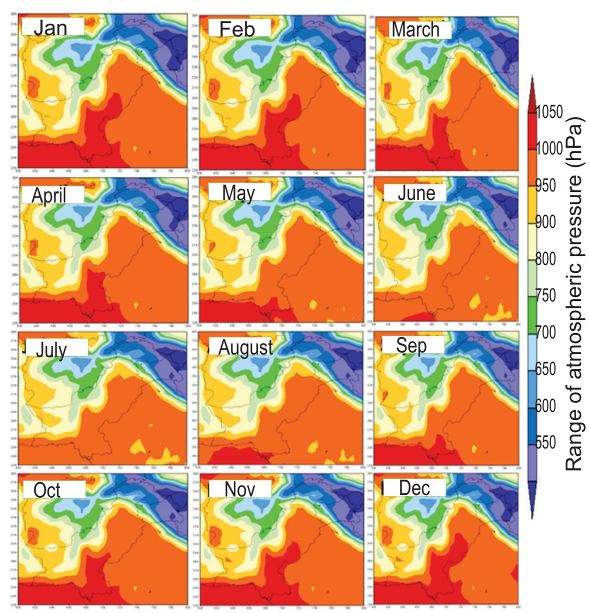

Fig. 3. Variation of atmospheric pressure (hPa) in Pakistan during 2018.

temperature is low (Fig. 2) which cool the air and kinetic energy of air molecules decreases. Cold air creates high air density and value of pressure increase.

Precipitation. Figure 4 shows annual relative precipitation in Pakistan during 2018. Maximum value of 30 mm/day is observed in July and lowest value of 0.1 mm/day is recorded in December. In summer and spring season (from March to July), precipitation level increase with increase in value of temperature. High temperature cause moisture in land and water to evapourate which add water droplets in atmosphere. Warm air rise water droplets and increase moisture level in air. These water droplets condense in upper troposphere and when they become heavy in clouds, they fall into earth surface as rain. Also, monsoon system enters in Karachi from Arabian sea and cause moderate and heavy rainfalls. In winter and autumn season especially in December, low temperature decrease value of precipitation by cooling air and reducing the rate of evaporation. Dry air does not rise in atmosphere and no rain occurs. Hence temperature and precipitation are directly proportional to each other.

Relative humidity. Figure 5 shows annual relative humidity in Pakistan during 2018. Maximum value of 60-70% is observed in August and lowest value of 10-15% is observed in April. In summer season (after May to August) in Karachi, value of temperature and precipitation is high which increase the concentration of water droplets in ambient air and monsoon currents from Bay of Bengal and Arabian sea generate rain and humidity level increase. In spring (from March to April) and autumn season (October and November) of Karachi, usually dry condition persists due to low precipitation level which decrease moisture level in air and relative humidity decreases. In winter season (after October to January) in Karachi, air remains cold due to low temperature and cold air has less capacity to absorb moisture than warm air therefore, it quickly saturates even with low moisture level and value of relative humidity increases. Hence temperature, precipitation and relative humidity are directly proportional to each other.

Wind speed and directions. Figure 6 shows annual wind speed and directions in Pakistan during 2018. Maximum value of 8-9 m/s is observed in July and lowest value of 1-2 m/s is observed in December. Wind speed increase from month of February to maximum in month of June at value of 8.1 m/s. After that, its value decrease upto January with lowest value observed in November at 4.1 m/s. In summer and spring season (from March to August) in Karachi, high temperature and low pressure (Fig. 2 and 3) warm the air and atmospheric lifting drives the wind to blow in high

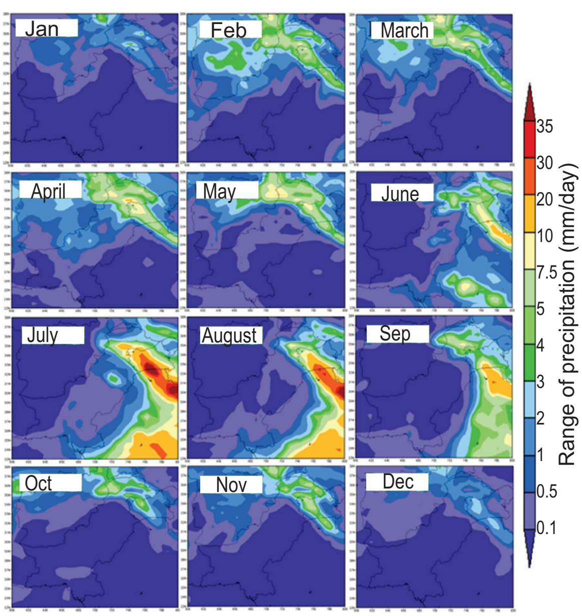

Fig. 4. Variation of precipitation (mm/day) in air of Pakistan during 2018.

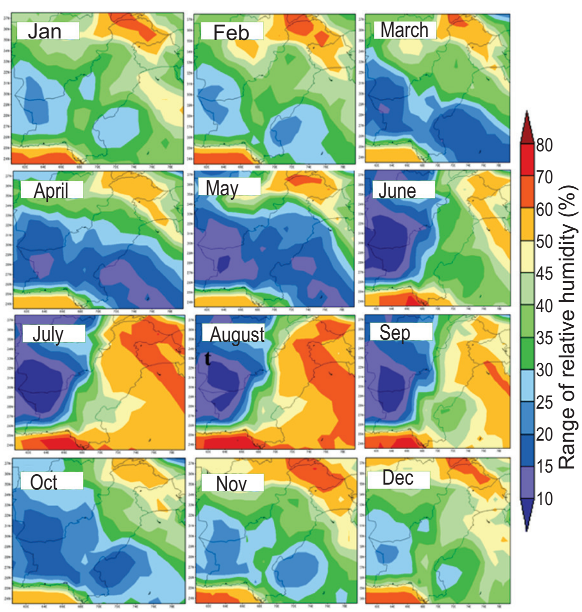

Fig. 5. Variation of relative humidity (%) in air of Pakistan during 2018.

speed from an area of high pressure to low pressure. Wind directions in these seasons are from sea towards Karachi and then move forward towards Hyderabad, Nawabshah. This phenomenon cause sea breeze to blow in Karachi and the wind speed increase. In winter and autumn season (from September to February), high pressure (Fig. 3) cause the wind to sink and low-temperature gradient (Fig. 2) decrease the speed of wind. Wind directions are from Nawabshah, Hyderabad to Karachi.

Sulphate mass concentration. Figure 7 shows annual mass concentration of sulphate in Pakistan during 2018. Maximum concentration of 21-23 µg/m^3 is observed in December and lowest concentration of 1-2 µg/m^3 is observed in August. Figure 8(A) shows that annual concentration sulphate ranges from 1.9 to 13 µg/m^3 with mean value of 4.67 µg/m^3. According to Fig. 8(B) concentration of sulphate started to decrease after the month of January to lowest concentration of 1.9 µg/m^3 in August. After that its value started to increase with maximum concentration of 13 µg/m^3 observed in December. High concentration in winter and autumn season especially in December was recorded which is due to burning of biomass in large quantity along with high emissions of vehicles and industrial units which release sulphate aerosols in high concentration Rizza *et al*. (2019). As shown in Fig. 4, minor rainfall due to low precipitation as well as low wind speed occurs in

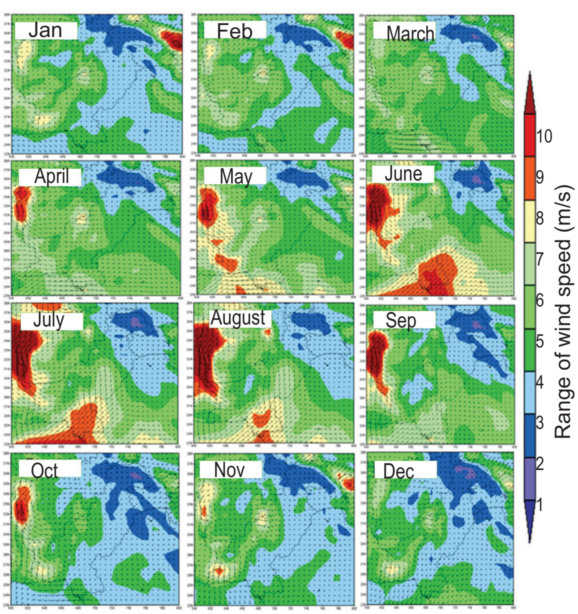

Fig. 6. Variation of wind speed (m/s) and its directions in Pakistan during 2018.

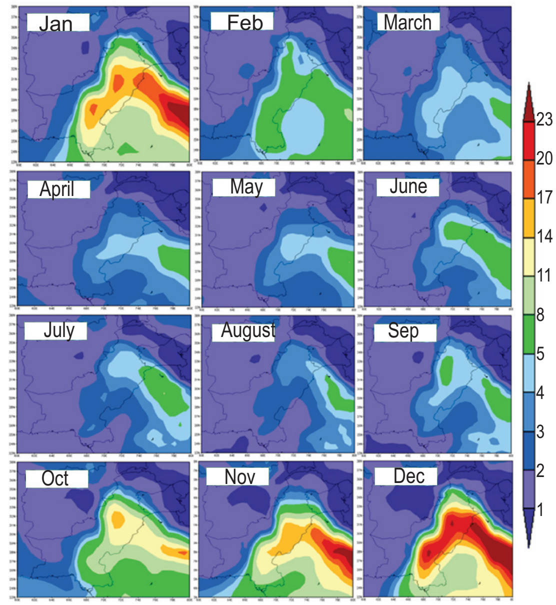

Fig. 7. Variation of sulphate mass concentration (µg/m^3) in air of Pakistan during 2018.

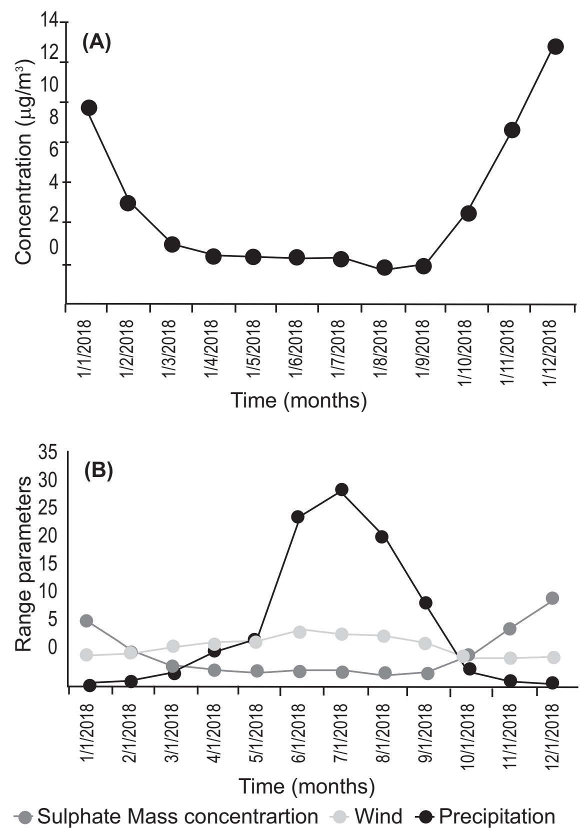

Fig. 8. Variation and correlation of sulphate mass concentration' wind speed, precipitation in air of Karachi.

these seasons which allows accumulation of pollutants and concentration of sulphate increases in ambient air. In summer and spring season especially in August, heavy rainfalls due to high precipitation level (Fig. 4) and monsoon system entering in these months cause the washing of atmosphere and high wind speed prevent accumulation of pollutants in ambient air and concentration of sulphate decrease. Hence sulphate mass concentration is inversely proportional to meteorological parameters (precipitation, wind).

sulphate density mass column. Figure 9 shows annual density mass column of sulphate in Pakistan during 2018. Mass concentration provides concentration of pollutants in troposphere, but column mass density provides concentration of pollutant from measuring instrument to the surface of earth (includes other Atmospheric layers than troposphere). Maximum value of 35-38 mg/m^2 is observed in December and lowest value of 5-8 mg/m^2 is observed in August. Figure 10(A) shows that annual density mass column of sulphate in Karachi ranges from 9.8 mg/m^2 to 24.5 mg/m^2 with mean value of 11.7 mg/m^2. Figure 10(B) shows that in winter and autumn season (after September to January), high column mass density of sulphate was recorded in ambient air of Karachi with maximum concentration of 24.5 mg/m^2 was recorded in January. This value is due to burning of biomass, exhaust of automobiles and fossil fuel combustion in industries that release CO_2, SO_2 and SO_4 along with other pollutants in high concentrations in atmosphere of Karachi Butt *et al*. (2018). Sulphur dioxide also reacts with molecules in air to produce sulphate aerosols Khokhar *et al*. (2016). These sulphate aerosols in troposphere cause ground-level haze and participate in smog and acid rain formation especially in winter season Butt *et al*. (2018). It also increases the earth albedo by reflecting solar radiations and produce health effects in humans like lungs irritation when inhaled in high concentration. In summer and spring season (after January to September), less quantity of sulphate mass density was recorded as compared to winter and autumn season with minimum value of 9.8 mg/m^2 recorded in the month of March. Sulphate aerosols are also released into the atmosphere by industrial and transportation activities Tariq *et al*. (2015) but high wind speed and monsoon rainfalls in summer and spring season (Fig. 4 and 6) wash the atmosphere and decrease the density of sulphate in ambient air. Hence values of wind speed and precipitation are inversely connected to each other.

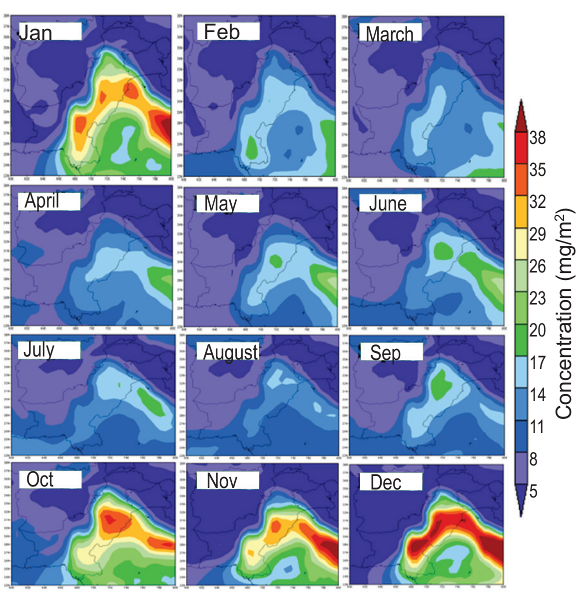

Fig. 9. Variation of sulphate density mass column (mg/m^2) in air of Pakistan during 2018.

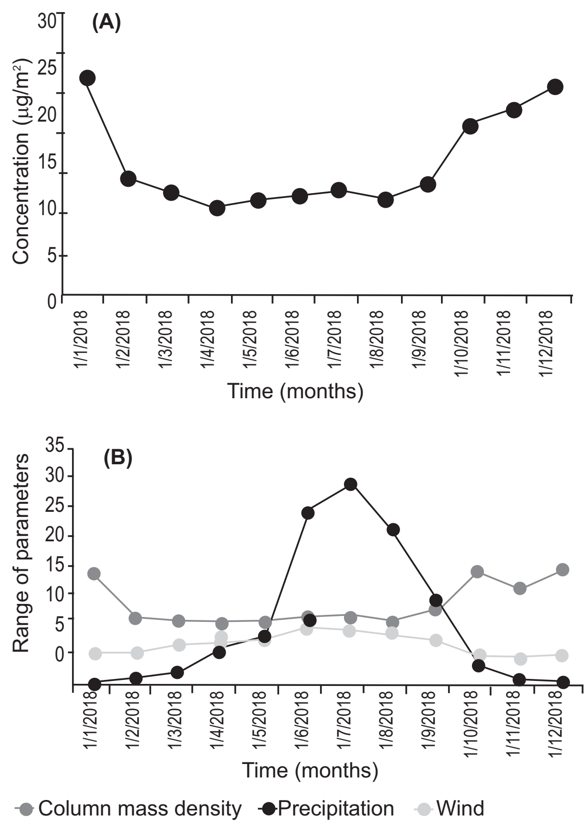

Fig. 10. Variation and correlation of sulphate density mass column, wind, precipitation in Karachi.

Sulphate extinction AOT 550 nm. Figure 11 shows annual AOT extinction of sulphate in Pakistan during 2018. Maximum value of 0.2-0.22 is observed in October and lowest concentration of 0.02-0.04 is observed in June. Figure 12 shows that annual AOT value in Karachi ranges from 0.06 to 0.18 with mean value of 0.10. Maximum value of 0.18 is observed in January and lowest value of 0.06 is recorded in the month of May. Extinction is the optical property of aerosol which describe the ability of scattering and absorption of solar and infrared radiations which change the earth albedo and air temperature. Extinction factor depend upon the mass density or concentration, wavelength and how strongly it absorbs those wavelengths Tariq *et al*. (2015). Extinction value of 0.01 means that air quality is good. If the value increases above 0.1, it means that hazy conditions started to form and value of more than 0.4 means air quality is highly degraded. In winter and autumn season (from October to January), biomass burning adds sulphate aerosols in troposphere which reflect upcoming solar radiations and increase the value of earth albedo causing global dimming Butt *et al*. (2018). But in troposphere it also causes hazy conditions in air which impair visibility and causes respiratory diseases when inhaled in high concentration Rizza *et al*. (2019). In summer and spring season, (from February to September) low biomass burning (especially after January) release sulphate aerosols in low concentration Tariq *et al*. (2015). Also, the amount of sulphate released from emissions of industrial and transportation sector into atmosphere is removed by high rainfall (Fig. 4) and wind patterns (Fig. 11) which move from sea towards Hyderabad and Nawabshah, transporting pollutants load away from Karachi. Therefore, extinction value of sulphate aerosols decreases in these seasons. Data of sulphate extinction AOT was extracted at 550 nm because sulphate aerosols give maximum reflectance at this wavelength Chin *et al*. (2002).

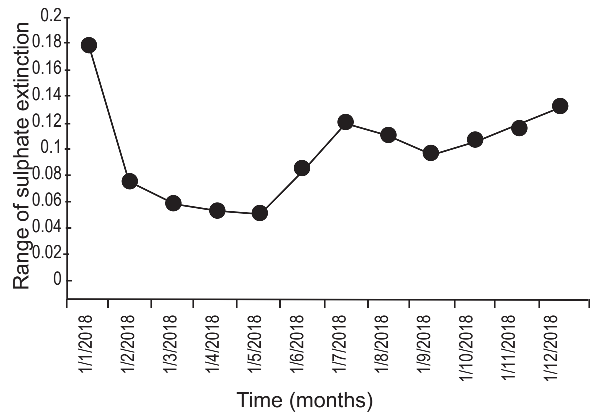

Fig. 12. Variation of sulphate extinction AOT at 550 nm in Karachi during 2018.

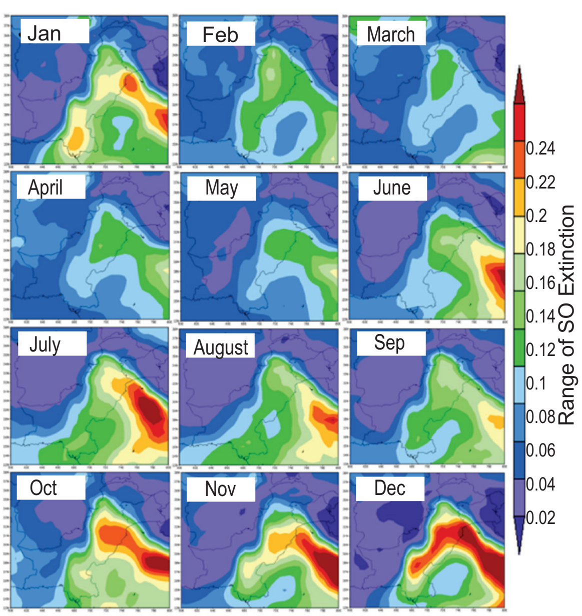

Fig. 11. Variation of sulphate extinction AOT at 550 nm in Pakistan during 2018.

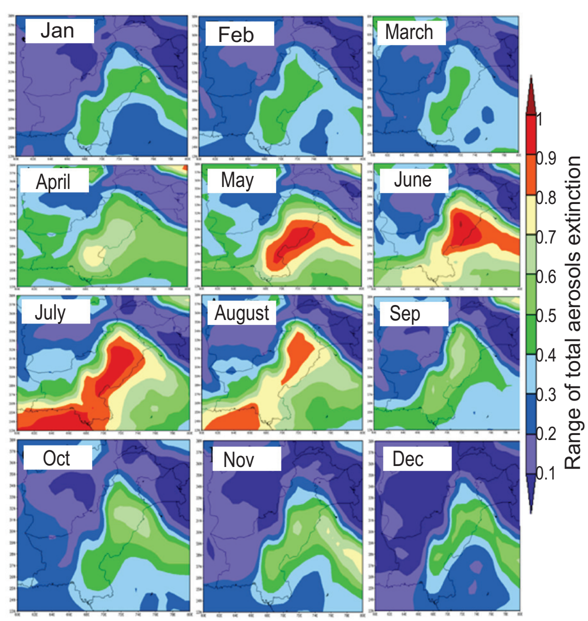

Fig. 13. Variation of total aerosol extinction at 550 nm in Pakistan during 2018.

Total aerosol extinction 550 nm. Maximum value of 0.9-1 is observed in July and lowest value of 0.1-0.2 is observed in March. Figure 14 shows that annual data of total aerosol depth in Karachi ranges from 0.3 to 0.9 with mean value of 0.52. Maximum value of 0.9 is observed in July and lowest value of 0.3 was observed in December. In summer and spring season (from April to September), high precipitation (Fig. 4) especially in July, add water vapours in large quantity in air of Karachi. Water vapours has the highest ability of absorbing and scattering solar radiations as compared to other atmospheric components Haywood *et al*. (2011). High wind speed (Fig. 6) transport desert dust from surrounding areas, mineral dust from suspension of minerals present in soil and sea salt Rizza *et al*. (2019) which is produced by evaporation of seawater due to high temperature (Fig. 2) which increase the concentration of aerosols (especially coarse size aerosols) in ambient air of Karachi and the extinction value cause by these aerosols also increase in these seasons Chin *et al*. (2002). In winter and autumn season (from October to March), biomass burning, fossil fuel combustion and transportation cause addition of aerosols (especially fine size aerosols) in air of Karachi (Khokhar *et al*., 2016) but due to low precipitation level (Fig. 4), concentration of water vapors is very low which decrease the value of total aerosol extinction in these seasons.

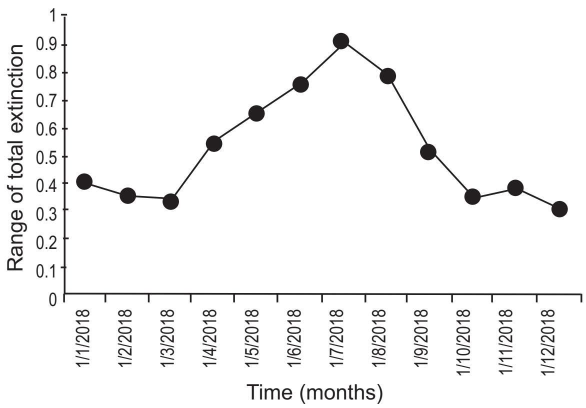

Fig. 14. Variation of total aerosol extinction at 550 nm in Karachi during 2018.

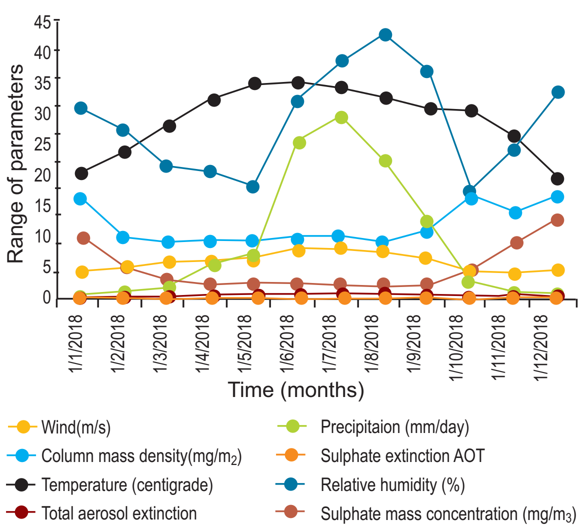

Fig. 15. Correlation of all meteorological and sulphate parameters in Karachi during 2018.

Figure 15 shows correlation of meteorological and sulphate parameters in Karachi. Analysis of graph shows that value of all meteorological parameters have increased in summer and spring season. Value of 44% relative humidity, 6 m/s wind speed, 34.7 °C temperature and 29 mm/day precipitation was recorded in this season in Karachi, whereas value of sulphate mass concentration (2.18 µg./m^3), sulphate density mass column (10.04 mg/m^2), sulphate extinction AOT (0.06) is low in this seasons. However, analysis of data extracted for winter and autumn season shows that lower values of temperature (19.6 °C), relative humidity (23%), precipitation (29 mm/day), wind speed (8.16 m/s) and higher concentration of sulphate mass concentration (9.76 ug/m^3), Sulphate density mass column (16.19 mg/m^2), sulphate extinction AOT (0.18) was recorded in these seasons. This clearly shows that sulphate aerosols and its optical properties are inversely proportional to meteorological parameters.

Conclusion

Sulphate aerosols play important part in climate change by reflecting solar radiations reaching earth surface causing global diming. Sulphate aerosols release from fossil fuel combustion in industries, biomass burning and from exhaust of automobiles. Sulphate aerosols in troposphere cause hazy conditions by impairing visibility and forming acid rain in atmosphere which effect buildings, metals, plants and acidify water bodies. They also cause health issues including lungs irritation in chronic heart patients and asthmatic (by bronchoconstriction). Data of sulphate aerosols extracted from Giovanni shows that in winter and autumn season column density and mass concentration of sulphate in ambient air is high due to burning of biomass (wood, agriculture residues, solid waste burning etc.) in large quantity and industrial emissions release pollutants in high concentration. Also, meteorological parameters including low precipitation or rainfall, high pressure and low wind speed favour the accumulation of pollutants in ambient air of Karachi, whereas in summer and autumn season of Karachi, biomass burning is low and pollutants released from industrial emissions are washed by rainfall in atmosphere. Also, high wind speed and low pressure prevent the accumulation of pollutants in ambient air. It is also observed that extinction factor of sulphate aerosols is usually low (0.2) during all seasons which prevents the formation of hazy conditions in Karachi during 2018. Meteorological factors (especially precipitation and wind speed) are inversely proportional to the concentration of sulphate aerosols in ambient air.

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Conflict of Interest. The authors declare they have no conflict of interest.

Reference

Ahmad, D., Zubair, A., Begum, A., Khan, M.U. 2014. Investigation and evaluation of ambient air quality in various parts of Karachi metropolitan city, Pakistan. *Middle East Journal of Scientific Research*, **21:** 234-243.

Ali, M., Tariq, S., Mahmood, K., Daud, A., Batool, A., Haq, Z. 2014. A study of aerosol properties over Lahore (Pakistan) by using AERONET data. *Asia-Pacific Journal of Atmospheric Sciences*, **50:** 153-162.

Brodowsky, C., Sukhodolov, T., Feinberg, A., Hopfner, M., Peter, T., Stenke, A., Rozanov, E. 2021. Modeling the sulphate aerosol evolution after recent moderate volcanic activity, 2008-2012. *Journal of Geophysical Research: Atmospheres*, **126:** e2021JD035472 1-24.

Butt, F.M., Shahzad, M.I., Khalid, S., Iqbal, N., Rasheed, A., Raza, G. 2018. Comparison of aerosol optical depth products from multi-satellites over densely populated cities of Pakistan. *International Letters of Natural Sciences*, **69:** 12-24.

Chin, M., Ginoux, P., Kinne, S., Torres, O., Holben, B.N., Duncan, B.N., Martin, R.V., Logan, J.A., Higurashi, A., Nakajima, T. 2002. Tropospheric aerosol optical thickness from the GOCART model and comparisons with satellite and Sun photometer measurements. *Journal of Atmospheric Sciences*, **59:** 461-483.

Chughtai, M., Mustafa, S., Mumtaz, M. 2014. Study of physico-chemical parameters of rainwater: a case study of Karachi, Pakistan. *American Journal of Analytical Chemistry*, **5:** 235-242.

Duncan, B.N., Martin, R.V., Staudt, A.C., Yevich, R., Logan, J.A. 2003. Interannual and seasonal variability of biomass burning emissions constrained by satellite observations. *Journal of Geophysical Research on Atmospheres*, **108:** 4040.

Hashmi, D.R., Shareef, A., Begum, R. 2018. A study of ambient air quality status in Karachi, by applying air quality index (AQI). *Pakistan Journal of Scientific and Industrial Research*, **61:** 106-114.

Hashmi, D.R., Shareef, A., Begum, R. 2017. Preliminary determination of air quality index (AQI) along busy roads in Karachi Metropolitan, Pakistan. *International Journal of Engineering Sciences and Research Technology*, **6:** 623- 633.

Hashmi, D.R., Shaikh, G,H., Usmani, T,H. 2005. Air quality in the atmosphere of Karachi city - an overview. *Journal of the Chemical Society of Pakistan*, **27:** 6-13.

Haywood, J.M., Bellouin, N., Jones, A., Wild, M., Shine, K.P., Boucher, O. 2011. The roles of aerosol, water vapour and cloud in future global dimming/ brightening. *Journal of Geophysical Research (Atmospheres)*, **116:** D20203: 1-24 DOI: 10.1029/ 2011JD016000.

Itahashi, S., Hatakeyama, S., Shimada, K., Takami, A. 2019. Sources of high sulphate aerosol concentration observed at Cape Hedo in spring 2012. *Aerosol Air Quality Research*, **19:** 587-600.

Jacob, D.J., Winner, D.A. 2009. Effect of climate change on air quality. *Atmospheric Environment*, **43:** 51-63.

Javid, K., Akram, N., Ranjha, M., Batool, R., Fiaz, A. 2018. Estimating aerosol optical depth (AOD) seasonal variability in Pakistan by using MISR. *Journal of Biodiversity and Environmental Sciences*, **13:** 40-45.

Kazi, A. 2014. Appraisal of air and water pollution in Hyderabad and Karachi, Pakistan. *Quaid-E-Awam University Research Journal of Engineering,* *Science and Technology*, **13:** 8-21.

Khan, M.K., Saied, S., Mohiuddin, S., Masood, S.S., Siddique, A., Hussain, M.M., Khwaja, H.A. 2017. Air quality assessment at industrial cum residential areas of Karachi city in context of PM2.5. *International Journal of Economic and Environment Geology*, **8:** 21-27.

Khan, M.N., Sarwar, A. 2014. Chemical composition of wet precipitation of air pollutants: A case study in Karachi, Pakistan. *Atmosfera*, **27:** 35-46.

Khjawa, H.A., Fatma, Z., Malashock, D., Aminov, Z., Kazi, A., Siddique, A., Qureshi, J., Carpenter, D.O. 2012. Effect of air pollution on daily morbidity in Karachi, Pakistan. *Journal of Local and Global Health Science*, **20:** 1-13.

Khokhar, M.F., Yasmin, N., Chishtie, F., Shahid, F. 2016. Temporal variability and characterization of aerosols across the Pakistan region during the winter fog periods. *Atmospheric Pollution Research*, **7:** 67.

Nafees, A.A., Taj, T., Kadir, M.M. 2012. Indoor air pollution ($PM_{2.5}$) due to secondary smoke in selected hospitality and entertainment venues of Karachi, Pakistan. *Tobacco Control*, **21:** 460-464.

Perera, F. 2017. Pollution from fossil-fuel combustion is the leading environmental threat to global pediatric health and equity: solutions exist. *International Journal of Environmental Research and Public Health*, **15:** 16. https://doi.org/10.3390/ijerph15010016

Randles, C.A., Silva, D.A., Buchard, V., Colarco, P.R., Darmenov, A.S., Govindaraju, R.C., Smirnov, A., Ferrare, R.A., Hair, J.W., Shinozuka, Y. 2017. The MERRA-2 aerosol reanalysis, 1980-onward, system description and data assimilation evaluation. *Journal of Climate*, **30:** 6823-6850.

Rienecker, M.M., Suarez, M.J., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., Bosilovich, M.G. 2011. MERRA: NASA's modern-era retrospective analysis for research and applications. *Journal of Climate*, **24:** 3624-3648.

Rizza, U., Mancinelli, E., Morichetti, M., Passerini, G., Virgili, S. 2019. Aerosol optical depth of the main aerosol species over Italian cities based on the NASA/MERRA-2 model reanalysis. *Atmosphere*, **10:** 709. https://doi.org/10.3390/atmos10110709

Takemura, T. 2020. Return to different climate states by reducing sulphate aerosols under future CO_2 concentrations. *Scientific Reports*, **10:** 21748: 1-7. https://doi.org/10.1038/s41598-020 78805-1

Tariq, S., Haq, Z. 2018. Ground-based remote sensing of aerosol properties over a coastal megacity of Pakistan. *Advances in Meteorology*, **3582191:** 1-12.

Tariq, S., Haq, Z., Ali, M. 2015. Analysis of optical and physical properties of aerosols during crop residue burning event of October 2010 over Lahore, Pakistan. *Atmospheric Pollution Research*, **6:** 969-978.

Yasmeen, Z. 2011. Inversion layer and its environmental impact over Karachi. *Pakistan Journal of Meteorology*, **7:** 53-62.