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Increased Shamal winds and dust activity over the Arabian Peninsula during the COVID-19 lockdown period in 2020

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A B S T R A C T

While anthropogenic pollutants have decreased during the lockdown imposed as an effort to contain the spread of the Coronavirus disease 2019 (COVID-19), changes in particulate matter (PM) do not necessarily exhibit the same tendency. This is the case for the eastern Arabian Peninsula, where in March–June 2020, and with respect to the same period in 2016–2019, a 30 % increase in PM concentration is observed. A stronger than normal nocturnal low-level jet and subtropical jet over parts of Saudi Arabia, in response to anomalous convection over the tropical Indian Ocean, promoted enhanced and more frequent episodes of Shamal winds over the Arabian Peninsula. Increased surface winds associated with the downward mixing of momentum to the surface fostered, in turn, dust lifting and increased PM concentrations. The stronger low-level winds also favoured long-range transport of aerosols, changing the PM values downstream. The competing effects of reduced anthropogenic and increased dust concentrations leave a small positive signal (\( <5 \text{ W m}^{-2} \)) in the net surface radiation flux (\( R_{\text{net}} \)), with the former dominating during daytime and the latter at night. However, in parts of the Arabian Gulf, Sea of Oman and Iran \( R_{\text{net}} \) increased by \( >20 \text{ W m}^{-2} \) with respect to the baseline period, owing to a clearer environment and weaker winds. It is concluded that a reduction in anthropogenic emissions due to the lockdown does not necessarily go hand in hand with lower particulate matter concentrations. Therefore, emissions reduction strategies need to account for feedback effects in order to reach the planned long-term outcomes.

1. Introduction

The Coronavirus disease 2019 (COVID-19) is widely known for its impacts on health and the economy (e.g., Ibn-Mohammed et al., 2021; Kaur et al., 2021). However, the policies aimed at restricting mobility and promoting social distancing in an attempt to control the spread of the virus also had an impact on the atmospheric and oceanic conditions through changes in the anthropogenic emissions. For example, a 7 % drop in the CO\textsubscript{2} emissions over a two-month period when most countries were in lockdown led to a reduction of the mean sea surface temperatures (SSTs) by roughly 0.5 °C in most coastal areas, with the SSTs in the north Indian Ocean decreasing by about 5 % (Al Shehhi and Samad, 2021). The clearer air also led to lower night-time land surface and air temperatures by up to 3 K, with urban areas experiencing a more pronounced reduction than rural ones in Europe and North America owing to the larger background values of anthropogenic pollutants. During daytime, on the other hand, the surface and air above were warmer due to less attenuation of the incoming shortwave radiation. The aforementioned changes, however, are highly heterogeneous owing to synoptic meteorological variability and varying surface properties (Parida et al., 2021). In more polluted environments the impact was even more dramatic: e.g., in the four major cities of India (Delhi, Kolkata, Mumbai, Chennai), the monthly mean temperature dropped by up to 3 K in April and May 2020 with respect to the 1980–2020 mean (Pal et al., 2021). The effects on the near-surface wind speed, on the other hand, were found to be a function of the strength of the wind: Ding et al. (2021), and over northern China, reported an increase in the frequency of wind speeds \( <1.5 \text{ m s}^{-1} \) but a decrease in the frequency of wind speeds in the range 1.5 to 3.5 m s\textsuperscript{-1}, also with a non-uniform vertical variability in the boundary layer (\( <250 \text{ m} \)). This is expected, as besides the larger-scale component, winds are a response to local-scale pressure gradients that are influenced by the temperature variation.

Several studies have reported the COVID-19 lockdown impacts on air quality, all stressing the cleaner environment (Sokhi et al., 2021). In the
United Arab Emirates (UAE), for instance, a country located on the south-eastern side of the Arabian Peninsula, there was a decrease in the concentration of pollutants such as nitrogen dioxide (NO₂), sulphuric dioxide (SO₂) and carbon monoxide (CO) by up to 40 % during the lockdown period (22 March to 24 June 2020) with respect to the pre-lockdown (01 January to 21 March 2020) values due to reduced emissions (Teixidó et al., 2021). However, the particulate matter (PM), both with those of a diameter of 10 μm or less (PM₁₀), and 2.5 μm or less (PM₂.₅), and ozone (O₃) concentrations actually increased by up to 45 %. The O₃ increase can be attributed to higher levels of solar activity during spring and the reduction in the concentration of nitrogen oxides (NOₓ) increase can be attributed to higher levels of solar activity during spring and the reduction in the concentration of nitrogen oxides (NOₓ) in urban areas, in line with the measurements at other sites such as in Kazakhstan (Kerimray et al., 2020), China (Zhao et al., 2020) and southern Europe (Picard et al., 2020). However, and as noted by Sokhi et al. (2021), the chemistry of O₃ is highly non-linear, as it depends on the ratio of volatile organic compounds to nitrogen oxides besides the presence of sunlight. The increase in the PM concentration, on the other hand, is unexpected. Published works reported a general reduction in particulate matter during the lockdown period, which exceeded 50 % at some sites (e.g., Arozgozes et al., 2021; Ding et al., 2021; Saario et al., 2021), owing to lower emissions and changes in precipitation and boundary layer height. However, Sokhi et al. (2021) noted that in a few cities in Europe and China the PM₁₀ increased due to long-range transport of dust. In fact, in Morocco the decrease in PM₁₀ by more than half due to reduced local emissions was offset by long-range transported aerosols (Otmani et al., 2020), highlighting the crucial role of non-local emissions. The increase in aerosol loading during the COVID-19 lockdown due to natural causes such as dust advection and bushfires has also been reported over India (Dumka et al., 2021), Greece (Kaskaoutis et al., 2021; Kokalis et al., 2021) and Australia (Zhao, 2020). Being one of the largest sources of mineral dust on Earth (Kok et al., 2021), and with mineral dust potentially accounting for >40 % of the PM₁₀ levels (e.g., Guan et al., 2019), it is important to understand the impact of the large-scale circulation on dust activity over the Arabian Peninsula (e.g., Francis et al., 2019) and hence its effects on the PM₁₀ concentrations during the lockdown period. As will be shown in this study, even though there was a reduction in anthropogenic emissions in the region during the lockdown period (Teixidó et al., 2021) as was the case elsewhere on the planet, the PM concentrations actually increased due to higher dust loadings. The main objectives of this study are to (1) investigate the dust activity over the Arabian Peninsula during the 2020 lockdown period; (2) identify the atmospheric conditions and patterns driving the observed dust activity; (3) highlight the role of dust aerosols in the observed particulate matter concentrations; and (4) assess the resulting radiative budget at the surface.

This paper is structured as follows. In section 2, the ground-based, satellite-derived and reanalysis datasets considered in this study are introduced and briefly summarised. In section 3 the focus is on the air quality over the Arabian Peninsula, while in section 4 the larger-scale atmospheric circulation is discussed. Section 5 details the radiative impacts of the anomalous aerosol loading in the region, with the main findings of the study summarised in section 6.

2. Data and methods

Ground-based measurements of meteorological and air quality fields collected by the UAE’s National Center of Meteorology and Environmental Agency - Abu Dhabi at two sites (Gayathi School and Bida Zayed; labelled as #4 and 5 in Fig. 1a) for the lockdown period (22-03-2020 to 24-06-2020) and baseline period (22-03 to 24-06 from 2016 to 2019) are used to inspect the local-scale changes due to the COVID-19 pandemic. In particular, the daily-mean PM₁₀ concentration and the hourly 10-metre horizontal wind speed are considered to check whether a link between the atmospheric pollution and the in-situ surface emissions is present. The choice of the lockdown period for the UAE is the same as in Teixidó et al. (2021) and is based on the existing preventive measures in place. The previous three years have been used as the reference period after ensuring high data availability (>90% of the study period). Other works such as Mazhar et al. (2021) also considered the three-year 2016–2019 as the reference period. In addition, hourly near-surface wind speed data at two airport stations in Kuwait and Iran, labelled as #1 and 2 in Fig. 1a, and wind speed profiles from upper air measurements at Al-Qaisumah, Saudi Arabia (#3 in Fig. 1a; Wyoming, 2019) are analysed to understand the upstream changes in wind speed.

Two satellite-derived products are employed: (i) the Clouds and Earth’s Radiant Energy System (CERES; Doelling et al., 2013; Doelling et al., 2016) SYN1deg (Ed4.1) clear-sky surface radiation fluxes, which provide shortwave, longwave and net radiation flux on a 1° × 1° grid every hour; (ii) Level 3 aerosol optical depth (AOD) at 550 nm from Moderate Resolution Imaging Spectroradiometer (MODIS) instrument onboard the National Aeronautics and Space Administration’s Terra (MOD08_D3 v6.1) and Aqua (MYD08_D3 v6.1) satellites. The AOD is available on a 1° × 1° grid and on a daily basis, and is calculated by combining the dark target (Kaufman et al., 1997) and deep blue (Hsu et al., 2004) algorithms for land and ocean.

Besides the observational measurements listed above, ERA-5 reanalysis data (Hersbach et al., 2020) is employed to understand the changes in the large-scale circulation during the lockdown period. This dataset has been found to perform well in the Arabian Peninsula (e.g., Fonseca et al., 2022; Francis et al., 2021), and its relatively high spatial (0.25° or ~27 km) and temporal (hourly) resolution make it suitable to be used here. While aerosols are not explicitly modelled in ERA-5, their effects are accounted for indirectly through the data assimilation system. For aerosol-related quantities, the Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA-2; Gelaro et al., 2017) data is employed. The model used to generate the latter reanalysis explicitly accounts for aerosols and their interactions with the climate system. MERRA-2 data is available on a 0.625° × 0.5° grid and on a 3-hourly basis for the period targeted in this work. This dataset also compares well with in-situ measurements in the target region (Roshan et al., 2019; Ukhov et al., 2020).

3. Air quality over the Arabian Peninsula

In this section the emphasis is placed on dust and PM₁₀ concentration over the Arabian Peninsula during the lockdown and baseline periods. Both the temporal mean and day-to-day variability are assessed using a combination of reanalysis, in situ measurements and satellite-derived data.

3.1. Dust activity

Dust emission increases over the Arabian Peninsula throughout the spring months as the surface dries out and the near-surface wind speed strengthens owing to a more vigorous sea-breeze circulation (Nelli et al., 2020). This is particularly true in La Nina years such as 2020, when a northward shift in the track of the mid-latitude baroclinic systems leads to drier conditions in the region (Yu et al., 2015), and resulting in enhanced dust lifting in the spring months. Fig. 1a shows the dust column mass density at 00 and 12 UTC over the Arabian Peninsula averaged over the lockdown and baseline periods and the difference between the two. The baseline maps show increased dust loading in an arc-shaped region extending from southern Iraq through Kuwait and to eastern and southern parts of Saudi Arabia, with a larger magnitude during daytime, and peaking over the Rub’ Al Khali desert. This region comprises the steepest pressure gradient between the subtropical high to the west and the monsoon trough to the east, which leads to stronger near-surface winds (and hence higher dust emissions) in particular during daytime when the pressure difference is the largest (Yu et al., 2016). There are also increased dust amounts in parts of Egypt and Sudan and southern Iran during daytime hours when the near-surface wind also has a larger magnitude as it is reinforced by local mesoscale
Fig. 1. In all panels, the first column shows the fields averaged over the lockdown period (22-03 to 24-06-2020), the second column over the baseline period (22-03 to 24-06, 2016 to 2019) and the third column gives the lockdown - baseline difference. (a) Dust column mass density (DCMD; g m$^{-2}$) from MERRA-2 at 00 and 12 UTC. The five stations referred in the discussion are marked with a circle in the rightmost panel of Fig. 1(a): 1. Kuwait International Airport; 2. Abadan, Iran; 3. Al-Qaisumah, Saudi Arabia; 4. Gayathi School; 5. Bida Zayed. (b) Hovmöller plot of DCMD averaged over the eastern Arabian Peninsula (45-57°E).
circulations such as the sea-breeze and topography-driven flows. During the lockdown period there was a reduction in dust loading over the western Arabian Peninsula, more pronounced in the southwestern Arabian Peninsula and adjacent Red Sea region. This arises from changes in the atmospheric circulation, as will be discussed in section 4. The remaining parts of the Arabian Peninsula exhibited dustier conditions, more pronounced over Iraq, Kuwait and adjacent Saudi Arabia as well as central and southern Oman, in line with findings by Anil and Alagha (2021). At night, the dustier conditions were restricted to Oman extending into parts of the UAE and Yemen albeit with a smaller magnitude with respect to the daytime values. These spatially-averaged maps, however, conceal a large day-to-day variability that is summarised in the Hovmoeller plots in Fig. 1b. They are averaged over 45°–57°E, capturing the region of increased dust over Iraq, Kuwait and Saudi Arabia. The higher dust loading in the referred region is mostly due to enhanced amounts from late March to early May, with the rest of

Fig. 2. Hovmoeller plot of 550 nm AOD (non-dimensional) from the MODIS instrument onboard the (a) Terra and (b) Aqua satellite averaged over 45–57°E. The white gaps denote missing data. White rectangles denote missing data. The conventions are as in Fig. 1.
the lockdown period featuring near-normal values. In the baseline period, the bulk of the dust activity takes place between 20°–30°N, extending to lower latitudes from the second half of May when the background northwesterly (Shamal) winds (e.g., Bou Karam Francis et al., 2017) strengthen and extend into southern parts of the Arabian Peninsula (Fonseca et al., 2022). In 2020, this transition took place roughly a week earlier. The reduction in dust loading in the 10°–20°N band at the end of May and beginning of June is due to the landfall of tropical depression ARBO1 over southwestern Oman and associated unstable weather conditions (Nastrallah, 2020).

Despite its reasonable performance over the Arabian Peninsula, MERRA-2 exhibits biases in particular due to missing emissions and deficiencies in the physics parameterisation schemes (Buchard et al., 2017). For this reason, it is important to assess it against satellite-derived estimates from MODIS found to be skilful over the region when compared to ground-based measurements, with MODIS Aqua AOD retrievals generally better than those of Terra (Ali and Assiri, 2019). Fig. 2a-b as are Fig. 1b but for the satellite-derived AOD. By and large, the MERRA-2 and MODIS plots are in close agreement with each other regarding the timing and spatial extent of the dust episodes both in 2020 and 2016–2019. In particular, the dustier conditions in the 20°–40°N latitude band from late March to early May and the earlier extension of the dustier environment to lower latitudes in 2020 with respect to the baseline period in May are present in both MERRA-2 and MODIS. This gives further confidence in the usage of MERRA-2 data for the analysis of aerosol-related fields in the Arabian Peninsula. A comparison of the MODIS Terra with the MODIS Aqua AOD estimates reveals that they are largely in agreement, with the latter generally having a higher magnitude probably because the satellite crosses the equator around 10 UTC (14 Local Time in the UAE) roughly three hours later than MODIS Terra when the dust loading is expected to be higher in the region (Yu et al., 2016).

3.2. Dust loading and particulate matter (PM) levels over the UAE

Fig. 3a shows the diurnal variability of the dust column mass density averaged over the UAE from MERRA-2. A comparison with Fig. 1b and 2a-b reveals that some of the dust episodes that affected the northern Gulf extended into the UAE: e.g., in late March (around 29 March) and late April to early May (from 27 April to 02 May). However, others missed the country, such as the one in early June that tracked further west, sparing most of the UAE. The baseline plot does not show a clear overall trend from late March to early June, with duster conditions in the local afternoon hours. The higher dust loadings around mid-May and late March arise from the fact that on individual years it was particularly dusty on those days, and hence the dust events’ signature is present in the three-year mean. Dust events that do not exhibit a diurnal cycle, like the one around 29 March 2020, are likely driven by larger-scale dynamics. Others, on the other hand, are characterised by an early morning (e.g., in late May to early June) or mid-afternoon (e.g., around 30 April and 10 May) peak in dust loading. They are driven by the downward mixing of momentum of the nocturnal low-level jet after sunrise (Todd et al., 2008; Bou Karam Francis et al., 2017) and the daytime sea-breeze circulation, respectively (Nelli et al., 2021).

As mineral dust is an important component of the particulate matter concentration, it is no surprise that duster regions exhibit higher amounts of PM (cf. Fig. 3b and 1a). However, dust is not the only source of particulate matter: crustal elements such as Silicone (Si), Sodium (Na), Aluminium (Al), Iron (Fe), Potassium (K) and Magnesium (Mg), as well as motor vehicle exhaust emissions and tyre abrasions also contribute to the PM values (Lenschow et al., 2001; Alghamdi et al., 2015), which are also a function of the meteorological conditions (Yin et al., 2016). Yu et al. (2015) notes that the soils in the southern Arabian Peninsula are rich in silt and clay which generates dust storms more easily than the sand desert in Saudi Arabia. The larger concentrations of crustal elements likely explain the higher PM values in this region compared to the DCMD values given in Fig. 1a for both the lockdown and baseline periods. However, the PM concentration and the DCMD spatial patterns are in close agreement, as dust is an important component of the PM in the Arabian Peninsula. Fig. 3c gives the time-series of PM10 at two sites in central-western UAE labelled as #4–5 Fig. 1a. The temporal mean PM10 value at the stations is around 150–200 μg m⁻³ for 2020 and 100–150 μg m⁻³ for 2016–2019. While the increase in PM10 concentration in the lockdown with respect to the baseline is roughly in line with that given by MERRA-2, the reanalysis dataset overestimates by a factor of 3 (~350 μg m⁻³) the observed magnitude at the two sites (not shown). This can be explained by its coarse spatial resolution and inherent deficiencies in emissions and parameterisation schemes (Buchard et al., 2017). Having said that, the peaks seen in the station data are also present in the diurnal variability plot given in Fig. 3a, in particular those that are likely triggered by larger-scale forcing (e.g., on 25–30 April 2020). It is interesting to note that, in spite of the higher magnitudes, the overall pattern of PM10 seen in the baseline period is largely present in 2020, with more quiescent conditions in April followed by more frequent dust episodes in May and June. This background variability is in line with the findings of Nelli et al. (2021). What is more, while in 2016–2019 the PM10 concentration at the location of the two stations closely follow each other, the atmosphere at Gayath School (#4 in Fig. 1a), located further west, is dustier in April and May while at Bida Zayed (#5 in Fig. 1a) larger values of PM10 are observed in June. This is consistent with a reduced clockwise shift and strengthening of the Shamal winds in June with respect to April and May (Bou Karam Francis et al., 2017), with the dust plumes extending further to the east. The increase in aerosol loading during the COVID-19 lockdown due to non-anthropogenic factors such as dust events reported here has also been noted elsewhere in particular over India (Dumka et al., 2021), Greece (Kaskaoutis et al., 2021; Kokkalis et al., 2021) and Australia (Zhao, 2020), in the latter in association with the bushfires in the 2019/2020 austral summer season.

4. Atmospheric circulation over the Arabian Peninsula

The atmospheric circulation over the Arabian Peninsula and on larger-scales over Eurasia is discussed in this section, in an attempt to better understand the variability of the aerosol-related fields presented in section 3.

4.1. Changes in Shamal winds

Fig. 4a shows the 925 hPa wind at 00 UTC and the 10-metre wind at 12 UTC for the lockdown and baseline periods and the difference between the two from ERA-5. The baseline map shows the southwest monsoon winds over the Arabian Sea, the northwesterly (Shamal) winds over the Arabian Gulf, and the topography-driven winds over parts of East Africa and Iran, the main large-scale circulation features in the region (Naizghi and Ouarda, 2017), with the sea-breeze circulation dominating in the daytime (12 UTC) plot. Over parts of Kuwait and northern Saudi Arabia at 00 UTC and western Iraq at 12 UTC, where there is higher dust loading in 2020 (Fig. 1a), the low-level wind speed is larger, which is consistent with increased dust emissions over this region (Fig. 1a). These stronger winds are driven by the downward mixing of momentum from the nocturnal low-level jet rising from a deeper boundary layer (Giannakopoulos and Toumi, 2012). In order to check whether this is the case, Fig. 4b-e give the vertical wind speed profile in the bottom 2.5 km at a nearby station in Saudi Arabia at 00 and 12 UTC. The downward mixing of momentum is clearly seen, with stronger winds at 00 UTC (03 local time, LT) when compared to 12 UTC (15 LT) in line with theoretical considerations (Washington and Todd, 2005; Giannakopoulos and Toumi, 2012). Similar findings are reached when inspecting the vertical wind shear plot (Fig. S1), which shows stronger winds at 850 hPa compared to 925 hPa at 00 UTC, whereas during daytime the shear is reduced owing to the deeper boundary layer and
Fig. 3. (a) Diurnal variability of the UAE-averaged DCMD (g m$^{-2}$) from MERRA-2. (b) PM$_{10}$ (μg m$^{-3}$) and PM$_{2.5}$ (μg m$^{-3}$) concentration at 00 UTC over the Arabian Peninsula from MERRA-2. (c) Time-series of weekly-mean PM$_{10}$ (μg m$^{-3}$) concentration at the location of Gayathi School (blue) and Bida Zayed (red) stations in the UAE labelled as #4 and 5 in Fig. 1a. The conventions are as in Fig. 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Fig. 4. (a) 925 hPa and 10-meter horizontal wind (the arrows give the direction and the shading gives the speed in m s\(^{-1}\)) for the lockdown period, baseline period, and the difference between the two from ERA-5. Wind speed (m s\(^{-1}\)) in the bottom 2.5 km from radiosonde profiles launched at Al Qaisumah station in Saudi Arabia, labelled as #3 in Fig. 1a, at (b) 00 and (c) 12 UTC, respectively. The conventions are as in Fig. 1.
associated enhanced vertical mixing. While such downward mixing is seen in the baseline plot (e.g. on 12 April and 10 May), these events are much more pronounced in the lockdown period, for which the low-level atmosphere is also more quiescent at 12 UTC. The inland location of this station means a reduced influence of land/sea-breeze circulations, with the strongest winds occurring earlier in the day in association with the low-level jet. The winds in the bottom 2.5 km were stronger here in the lockdown period with respect to the baseline period which is consistent with the enhanced surface winds seen in Fig. 4a and dust loading given in Fig. 1a.

An inspection of the day-to-day variability in the surface wind speed is presented in Fig. 5a-b for a station in Kuwait and Iran labelled as #2 and 1 in Fig. 1a, respectively. In the baseline period there is a gradual increase in the near-surface wind speed from late March to late June, as the pressure gradient between the monsoon trough to the east and the subtropical high to the west builds up in the summer months (Al Senafi and Anis, 2015; Yu et al., 2016). The weaker winds at Abadan may reflect its inland location compared to the coastal Kuwait International Airport. The peak in surface wind speed at both sites is during morning hours and early afternoon, which is consistent with the downward mixing of momentum from the nocturnal low-level jet winds seen in Fig. 4b-c, as the build-up of the boundary layer starts a few hours after sunrise. Additionally, the daytime land-breeze may reinforce the background northwesterly winds, although the synoptic forcing may overwhelm the local mesoscale circulations (Alsarraf and Van Den Broeke, 2015). The near-surface winds were stronger during the lockdown period, in line with the time-mean plots in Fig. 4a, with the timing of the events matching the peaks in dust column mass density given in Fig. 1b and 2a-b. At upper-levels in the atmosphere the winds were also larger compared to 2016–2019. This can be seen in Fig. 5c, with the peak in wind speed in both the lockdown and baseline periods between 9 and 14 km corresponding to the subtropical jet which in April/May is over northern Saudi Arabia before shifting polewards in June when the upper-level winds weaken at the site (Martius, 2014). Figs. 4 and 5 highlight the increased dust emissions over parts of Iraq and Saudi Arabia, but its subsequent transport downstream into the UAE is not obvious as the time-mean wind speed over the Arabian Gulf was actually lower in March-June 2020 with respect to the reference period (Fig. 4a).

However, an inspection of the day-to-day variability (Fig. S2) reveals that there were periods when the northwesterly wind was stronger such as in mid- to late-April (around 10 May) and in late-May to early-June, around the time when the PM concentration was higher at the two stations in eastern UAE (Fig. 3c). As a result, the higher PM values in the UAE are associated with dust that was lifted in the northern Arabian Gulf and subsequently transported downstream by the Shamal winds. Such a dust advection mechanism in the region is well-known and has been extensively discussed in the literature (e.g. Basha et al., 2015; Karagulian et al., 2019).

The fact that the winds were stronger throughout the whole column in 2020 as shown in Fig. 5, in particular from late March to mid-May, suggests the presence of an anomalous large-scale atmospheric circulation over the region when compared to the baseline period. This is investigated in the next sub-section.

4.2. Large-scale atmospheric circulation

Fig. 6a shows the upper and low-level streamfunction over Eurasia for the lockdown and baseline periods and the difference between the two. The corresponding wind speeds are given in Fig. 6b. The baseline plot shows the subtropical jet extending from North Africa into Asia at 200 hPa, and the eddy-driven jet that splits over western Europe, with the northern branch converging with the subtropical jet over East Asia (Woollings, 2010). The 700 hPa streamfunction plot shows the subtropical high over Africa extending over the Arabian Sea into southern parts of India (Spinks et al., 2015) while at upper-levels, the marked poleward decrease associated with the subtropical westerly jet is the dominant feature. An equivalent barotropic wavetrain is seen over Europe and northern and central parts of Asia that resembles the negative phase of the Scandinavian pattern (Bueh and Nakamura, 2007) in the difference plot, with the anomalous high pressure over parts of Russia leading to a southward displacement and strengthening of the subtropical jet. This is consistent with the stronger upper-level winds at Al Qaisumah in northern Saudi Arabia (Fig. 5c). At 700 hPa, a level located roughly 3 km above sea-level where the low-level jet is found in the Arabian Peninsula (Giannakopoulou and Toumi, 2012), the wind speed also increases over the majority of Saudi Arabia with respect to the reference period. This increase is explained by a westward shift of the subtropical high, which during this time of the year typically extends into India (Spinks et al., 2015) but in the lockdown period only reached the Arabian Peninsula (Fig. 6a). The streamfunction anomalies in Fig. 6a over southern Asia comprise a quadrupole, with a pair of anticyclones over the western side and cyclones over the eastern side at upper-levels and the opposite at lower-levels. This suggests that the anomalous atmospheric circulation is likely a response to a tropical forcing (Jin and Hoskins, 1995). This is confirmed in Fig. 6c which shows the corresponding velocity potential maps. The divergent wind is given by the gradient of the velocity potential, meaning that negative values indicate divergence and positive values indicate convergence. In the baseline period most of the convection takes place over Southeast Asia, shifting northwards during spring in line with the annual march of the Sun, with suppressed convection in northern and southern parts of Africa where the subtropical anticyclones play a dominant role in the weather conditions (Tanaka et al., 2004). In the lockdown period there was enhanced low-level convergence and upper-level divergence (i.e. more active convection) with respect to 2016–2019 over the tropical Indian Ocean, mostly on the eastern side extending into Southeast Asia, where the increased precipitation can be seen in Fig. 6d which gives the precipitation rate at 00 and 12 UTC. The precipitation field is noisier than the velocity potential in particular over land due to the influence of the complex topography and local-scale circulations, while the velocity potential is largely aligned with tropospheric heating anomalies (Qian, 2008). The precipitation maps for the baseline period show the contrast between the daytime peak over land regions and the nighttime maximum over the surrounding oceans and seas in response to the sea-/land-breeze circulations and their interactions with the background flow and topography-driven flows (e.g. Im and Eltahir, 2018). Rainfall is also enhanced over the high terrain (e.g. Ethiopian Highlands, Sarawat mountains in Yemen and western Saudi Arabia, mountainous terrain in Turkey and Iran) during daytime when the strong solar heating and upslope winds favour convective activity. The wetter conditions during the lockdown period also extended into India, where the summer monsoon was more active during in 2020 than in the previous years due to the reduction of pollutants over the Indian subcontinent and south-east Asia (Fadnavis et al., 2021). The higher amounts of precipitation over southern parts of Oman are due to tropical depression ARB01 that affected the region in late May to early June (Nasrallah, 2020). On the other hand, over the mountainous terrain in western Saudi Arabia and coastal Eritrea and Sudan there was less precipitation in the lockdown compared to the reference period. As a result of the reduced cloud cover and increased amount of surface solar radiation, the daytime upslope flow will be stronger. Together with the weaker low-level winds from the Gulf of Aden to the Red Sea, in particular at 00 UTC (Fig. 4a), there is anomalous low-level wind divergence over the Red Sea which is consistent with the lower aerosol loading over the different regions (Fig. 1a and 3b). The impact of low-level wind convergence/divergence on the aerosol concentration is noted in Rashki et al. (2019), who report that the higher aerosol loadings in the northern and central Arabian Sea in the summer season are due to the low-level convergence of the southwesterly monsoon winds, the northwesterly Shamal winds from the Arabian Gulf, and the northeasterly Levant winds from Iran along the Intertropical Discontinuity. While low-level aerosol-rich air masses converge there is an increase in the aerosol...
Fig. 5. Diurnal variability of the 10-metre wind speed (m s$^{-1}$) at (a) Kuwait’s International Airport in Kuwait, and (b) Abadan’s Airport in Iran. These stations are labelled as #1 and 2 in Fig. 1a, respectively. (c) Wind speed vertical profile (m s$^{-1}$) from radiosondes launched at Al Qaisumah station in Saudi Arabia, labelled as #3 in Fig. 1a, from the surface to 20 km altitude at 00 UTC. White boxes denote missing data. The conventions are as in Fig. 1.
loading/concentration, when they diverge the air becomes clearer as there is an increased mixing with less dusty air.

Fig. 6 shows that the atmospheric response to enhanced convection over the tropical Indian Ocean and the wavetrain over higher-latitudes led to a westward displacement of the subtropical high over Africa and the Middle East and a southward shift in the position of the subtropical jet in the region. These circulation changes explain the stronger winds throughout the troposphere seen in radiosonde profiles over northern Saudi Arabia and neighbouring Iraq and Iran (Figs. 4 and 5) which led to higher dust emissions locally, and the subsequent transport
of dust into the UAE and surrounding region.

5. Radiative impacts over the Arabian Peninsula

The anomalous aerosol loading observed during the lockdown period (Fig. 1a and 3b-c) will have an impact on the surface radiation budget. This is summarised in Fig. 7 which shows the surface clear-sky short-wave, longwave and net radiation (R_{net}) fluxes over the UAE and surrounding region as estimated from satellite measurements. The upward longwave radiation flux is largely controlled by the surface temperature, and hence during daytime it is higher over land owing to the lower thermal inertia and strong surface heating while at night the largest values are seen over the Arabian Sea which is warmer than the Arabian Gulf during the spring months (Nesterov et al., 2021). The highlands over Iran have the lowest upward longwave radiation fluxes as a result of the colder surface temperatures. As noted by Nelli et al. (2020), the downward longwave radiation flux is essentially a function of the emissivity of the atmosphere which in turn depends on the atmospheric composition including aerosols and water vapor (Francis et al., 2020), and exhibits a smaller amplitude diurnal cycle compared to the downward longwave radiation flux. It is larger over the water bodies at night whereas at 12 UTC it peaks in parts of Oman where the sea-breeze brings in the more moist marine air inland. The surface downward shortwave radiation flux at 12 UTC shows a west-to-east gradient, as by that time the Sun is already to the west of 45 E, while the upward shortwave radiation flux is controlled by the albedo which is very small over the water bodies and larger ~ 0.33 over desert regions (Csiszar and Gutman, 1999). The R_{net} fluxes are dominated by the shortwave fluxes during daytime and are equal to the net longwave fluxes at night (Fig. 7).

Dust aerosols are known for scattering and absorbing the Sun’s
Fig. 7. (a) Downward and upward surface longwave radiation flux (W m\(^{-2}\)) at 00 and 12 UTC and net longwave radiation flux at 12 UTC for the domain 45°-65° E and 20°-30° N from CERES. (b) as (a) but for the surface shortwave radiation flux at 12 UTC only. (c) Surface net radiation flux (Rnet) at 00 and 12 UTC. The conventions are as in Fig. 1.
shortwave radiation flux, leading to a decrease in its surface values, and for trapping the longwave radiation and emit it back toward the Earth’s surface (Prakash et al., 2015; Francis et al., 2022a; Francis et al., 2022b). Greenhouse gases such as SO2 and NO2, which decreased during the lockdown period, including in the UAE (Teixido et al., 2021), have a similar effect on the surface’s radiation budget (Chang et al., 2009). As the aerosol loading increased (Fig. 3b) and the concentration of anthropogenic greenhouse gases decreased, the net effect on the surface radiation budget is expected to be small due to competing effects between natural and anthropogenic components. This is confirmed when inspecting $R_{net}$ (Fig. 7c), which exhibits changes generally within $\pm 5$ W m$^{-2}$.

A deeper look at the fluxes reveals an increase in the surface net longwave radiation flux in the UAE by up to $5$ W m$^{-2}$ whereas the net shortwave radiation flux also rises marginally over the country. A comparison with the PM10 spatial pattern, Fig. 3b, suggests that higher amounts of aerosols account for the increase in the longwave radiation flux at night, whereas the higher net shortwave flux, Fig. 7b, which has a larger magnitude around Abu Dhabi ($\sim 10$ W m$^{-2}$), likely arises from reduced anthropogenic forcing. The resulting warmer surface and air temperatures (not shown) are then consistent with the increased daytime longwave radiation flux, Fig. 7a. The changes in the surface radiation fluxes reported here are in line with those estimated by Mazbar et al. (2021) using the same dataset but for globally averaged fields and by Kokkalis et al. (2021) over Greece. It is interesting to note that over the Arabian Gulf, Sea of Oman and adjacent Arabian Sea there is a general increase in $R_{net}$ at both 00 and 12 UTC with peak values of 7 W m$^{-2}$ and 20 W m$^{-2}$, respectively. A possible explanation is that the weaker low-level wind speeds over the region, Fig. 4a, lead to reduced amounts of aerosols (Fig. 1a and 3b), with the clearer air allowing for higher levels of shortwave radiation reaching the surface. The large ($\sim 20$ W m$^{-2}$) increase in $R_{net}$ at 12 UTC over parts of Iran arises from a higher shortwave radiation flux, Fig. 7b, and is due to weaker anthropogenic forcing and near-surface wind speeds as well as more moist weather conditions (Broomandi et al., 2020).

6. Discussion and conclusions

In this study, the impacts of the changes in the dust activity in the Arabian Peninsula during the COVID-19 lockdown is investigated using a combination of in-situ, satellite-derived and reanalysis data. The lockdown period is defined as 22 March to 24 June 2020 with the baseline period comprising the same days but for 2016–2019. With respect to 2016–2019, the dust loading during the lockdown period was higher over the major portion of the eastern Arabian Peninsula with hotspots in dust loading over Kuwait, Iraq and neighbouring Saudi Arabia. This tendency was seen in both the reanalysis and satellite-derived aerosol loading. An inspection of the larger-scale circulation indicated a strengthening of the nocturnal low-level jet, in particular over northern Saudi Arabia, with the subtropical jet also being stronger in the region and displaced southwards when compared to the baseline period. These anomalies are a response to enhanced tropical convection in the Indian Ocean which was linked to the effects of the lockdown over the Indian subcontinent on the Indian summer Monsoon (Kripalani et al., 2022). These anomalies were modulated by a wavetrain in the mid-latitudes, with an anomalous ridge over parts of Russia also contributing to the shift in the upper-level jet. At the near-surface level, the largest wind speed increases were around Kuwait, Iraq and northern Saudi Arabia, which induced large dust emissions contributing to the observed anomalous dust loadings over this region.

Dust aerosols are the main contributor to particulate matter (PM) concentrations especially in regions close to major dust sources such as the Arabian Peninsula. The long-range transport of aerosols can explain the increased PM values downstream. Enhanced dust activity during the lockdown period explains the observed increase in PM concentrations along the eastern part of the Arabian Peninsula, extending from Iraq to southern Oman. The peaks in dust loading go hand in hand with the peaks in PM10, most of which were associated with synoptic-scale forcing. The increased dust emission was driven by high near-surface winds that arise from the downward mixing of momentum from the nocturnal low-level jet to the surface in response to the daily build-up of the boundary layer after sunrise. The downward mixing of higher momentum aloft was observed in radiosonde profiles over northeastern Saudi Arabia where enhanced dust loadings were seen. Such episodes were stronger and more frequent in the lockdown period, in line with the more active nocturnal low-level jet Shamal winds.

Besides the changes in atmospheric circulation, the radiative impacts at the surface of the anomalous aerosol loading in the lockdown period were also investigated. Over the United Arab Emirates (UAE) and surrounding region, two competing factors were at play; (i) higher amounts of dust aerosols and (ii) reduced greenhouse gas concentrations. The former was evident at night, when the surface net longwave radiation flux was up to $5$ W m$^{-2}$ larger with respect to the baseline period, as aerosols act to absorb and re-emit back to the surface the thermal radiation. The radiative effects of the lower amounts of pollutants were mostly seen during daytime, as evidenced by the higher amounts of net shortwave radiation in particular around Abu Dhabi ($\sim 10$ W m$^{-2}$). Overall the changes in surface radiation fluxes were generally small ($\sim 5$ W m$^{-2}$), with the largest values ($\sim 20$ W m$^{-2}$) seen over the water bodies and parts of Iran, owing to weaker wind speeds and aerosol loading. These reduced radiative changes are in line with the global study of Mazbar et al. (2021) who made use of the same satellite-derived dataset.

While the reduction in the concentration of pollutants such as SO2, NO2 and CO during the COVID-19 lockdown has been widely reported, in the vast majority of the published studies the particulate matter concentration also decreased. Over the eastern Arabian Peninsula, however, it actually increased due to a more active wind flow in response to anomalous tropical forcing. This highlights the complex nature of dust emissions and its relationship to anthropogenic and natural forcings. Having less man-made pollutants, therefore, does not necessarily mean having a cleaner environment. Hence, it is essential that dust aerosols and their feedback on the regional climate should be considered when establishing national and regional strategies for anthropogenic emission reduction.

CRediT authorship contribution statement

Diana Francis: Conceptualization, Formal analysis, Writing – review & editing, Funding acquisition, Methodology, Project administration, Supervision. Ricardo Fonseca: Data curation, Investigation, Formal analysis, Writing – original draft. Narendra Nelli: Visualization, Software, Data curation, Investigation, Formal analysis. Oriol Teixido: Resources, Validation, Formal analysis. Ruqaya Mohamed: Resources, Validation, Formal analysis. Richard Perry: Validation, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aeolia.2022.100786.

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