1. Introduction

Atmospheric aerosols have a wide range of impacts on the climate system. This includes interactions with the incoming solar radiation and clouds (Forkel et al., 2012), serving as a medium for transporting various organisms through vast distances (Azua-Bustos et al., 2019), and causing or enhancing respiratory, infectious, cardiovascular, and allergic diseases (Boersma et al., 2008). However, quantifying the effects of aerosols on the climate on both global and regional scales has never been a trivial problem, primarily due to their sporadic nature and large spatiotemporal variability (Boucher et al., 2013).

Atmospheric aerosols originate from different sources, namely biogenic (nature) and anthropogenic (human-related activities). Mineral dust aerosols are the dominant species in the atmosphere by virtue of their large contribution to the global aerosol loading (Tegen et al., 2002). These natural aerosols originate mostly from the Arabian, the Asian, and the Sahara deserts (Prospero, 2002). Dust mixed with biomass burning and urban pollution, frequently labeled as “polluted dust,” is also an important contributor to atmospheric aerosols and is regularly observed in the Middle East, West Africa, and Central Asia (Kim et al., 2018).
known as the Arabian heat low (Schwitalla et al., 2020). In addition, the strong nighttime radiative cooling, especially in the cold months, can lead to the formation of fog (Chaouch et al., 2017; Gandhidasan & Abualhamayel, 2012; Mohan et al., 2020; Nelli et al., 2020a; Temimi et al., 2020; Weston et al., 2018), which is often a hazard for road and air traffic in the region (Aldababseh & Temimi, 2017). The atmosphere in the interior areas of the Arabian Peninsula is rather dry year-round, which is favorable for the occurrence of dust storms (Nelli et al., 2020a; Yu et al., 2015), although strong evaporation over the Arabian Gulf and Sea of Oman can lead to specific humidities in excess of 20 g kg$^{-1}$ locally (P. Xue & Eltahir, 2015), with this very moist air advected inland by the daytime sea-breeze circulation.

Given the large spatial spread of atmospheric aerosols, satellite-based observations are essential to investigate their variability. Over the past few years, space-based instruments such as the Moderate Resolution Imaging Spectroradiometer (MODIS; Kaufman et al., 1997; Salomonson et al., 1989), Multispectral Imaging Spectroradiometer (MISR; Diner et al., 1998), Ozone Monitoring Instrument (OMI; Levelt et al., 2006), and Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO; Winker et al., 2003), have helped to measure aerosols in the atmosphere and further improve understanding of their impacts. CALIPSO has the additional advantage of detecting the altitude of atmospheric aerosols in clear sky conditions, beneath cirrus clouds, as well as over bright surfaces, when compared to the passive satellite sensors (e.g., MODIS, MISR, OMI), which can only give total column values (B. Liu et al., 2018).

Long-term and global aerosol measurements with space-borne instruments are crucial for a better understanding of aerosol distribution and consequently their effects on the environment (Hansen et al., 2000). Consequently, there is a need to evaluate the accuracy of satellite observations against ground-based measurements, especially near source regions. In particular, the Aerosol Robotic Network (AERONET), a collection of sun photometers spread out all over the whole world (Holben et al., 1998), has been used in a number of studies to validate satellite observations of atmospheric aerosols (Bibi et al., 2015; Kokhanovsky et al., 2007; Levy et al., 2010; C. Liu et al., 2014; Ogunjobi & Awoleye, 2019; Omar et al., 2013). The intercomparison between the aforementioned two sets of measurements is commonly made through the Aerosol Optical Depth (AOD), a measure of the attenuation of the incoming solar radiation as it goes through the atmosphere due to the presence of aerosols (Holben et al., 1998). A value of zero indicates no attenuation, whereas the value of AOD = 1 corresponds to the decrease in the shortwave radiation flux at the surface by the factor of $e$ compared to that at the top of the atmosphere.

The United Arab Emirates (UAE) is a relatively flat country, except on the northeastern side where the Al Hajar mountains rise to nearly 1800 m above sea level. It features a hot desert-type climate, with annual average rainfall amounts ranging from 40 mm in the southern desert to 160 mm in the Al Hajar mountains (Niranjan Kumar & Ouarda, 2014; Wehbe et al., 2017, 2018). It is surrounded by the Arabian Gulf to the north and west, and by the Rub‘Al Khali desert to the south. Being located on the fringes of the Arabian Desert, which is the second largest dust source at global scale (Francis et al., 2019; Prospero, 2002), the UAE is impacted year-round by dust storms. In the summer, the superposition of local winds on top of the monsoon flow may prevent or hinder advection of aerosols from the region, as noted by Rashki et al. (2019). The combined presence of strong thermal inversions and multiple dust layers in the vertical direction can lead to anomalous atmospheric conditions at the near-surface level (Weston et al., 2020). In addition to dust, other types of aerosol can be found over the region originating from both local emissions and long-range transport (Kim et al., 2018). Despite being a significant source of aerosol loading, few studies have been dedicated to the characterization of the atmospheric composition and its variability over the Arabian Desert and more particularly over the UAE, where aerosol loading has been increasing in recent years (Aldababseh & Temimi, 2017; Francis et al., 2019; Hamidi et al., 2013). Therefore, there is still a need for a better understanding of aerosol variability over the UAE on different time scales (diurnal, seasonal, and interannual).

With the aim of understanding the vertical distribution of aerosols in the UAE, and its coupling with the meteorological conditions, the UAE Unified Aerosol Experiment (UAEx) field campaign was conducted in the summer of 2004 (Reid et al., 2008). The analysis of data collected from 18 flights revealed that mesoscale circulations, such as land- and sea-breezes, play an important role in the vertical distribution of aerosols in the region. In particular, the stable marine boundary layer is able to trap dust, pollution, and smoke at very low levels, while the presence of vertical shear can lead to additional aerosol layers above. Without vertical wind shear, however, the aerosol concentration is more uniform with height. More recently, Filiglou
et al. (2020) performed a comprehensive analysis of the properties of aerosols in the UAE for a 1-year period from March 2018 to February 2019. The authors used nighttime measurements from a ground-based Raman Light Detection and Ranging (LIDAR) instrument located at Al Dhaid, a site located roughly 70 km to the east-northeast of Dubai. They detected several aerosol layers in the lower 11 km of the atmosphere associated with a mean aerosol depth in the range from 0.25 to 0.49 at 355 nm and from 0.10 to 0.32 at 532 nm wavelengths, respectively. The optical properties of the observed mineral dust at the site were found to be similar to those of the African dust. The only observed differences were found in the real refractive index. This is likely due to a higher potassium concentration in the soils of the Arabian Peninsula. They also found that the AOD values were higher in the summer months when the near-surface wind is stronger. This is in line with other published work (Naizghi & Ouarda, 2016; Nelli et al., 2020a, 2020b).

While there are aerosol-related studies in the UAE (Basha et al., 2015; Francis et al., 2020; Karagulian et al., 2019), they generally focus on individual events. The lack of a longer-term analysis of the spatial and temporal variability (the latter on diurnal to interannual time scales) and the characteristics of the aerosols in the region has motivated this study. Such an investigation will serve as the basis for future regional-scale and modeling aerosol research in the eastern Arabian Peninsula. The approach adopted in this study is as follows. First, the measurements of CALIPSO AOD for 14-years (2006–2019) are assessed against those collected at two AERONET stations, one coastal and another deep in the inland desert. Then the spatial and temporal variabilities of the AOD are analyzed to gain insight on the aerosol loading variability at the diurnal, seasonal, annual, and interannual time scales.

This paper is structured as follows. In Section 2, an overview of the study area and of the observational datasets considered, is given. The methodology is described in Section 3, while in Section 4 a summary of the prevailing synoptic conditions in the UAE is provided. The climatology of atmospheric aerosols over the UAE is discussed in Section 5, and is followed by an analysis of the variability of the AOD on diurnal, seasonal, and interannual scales in Section 6. Finally, the main findings of this study are outlined in Section 7. The findings of this work are applicable to other areas in the Middle East as well, and they will help to improve the existing knowledge on the distribution and the variability of aerosols.

2. Datasets

2.1. Observational Datasets

2.1.1. Ground-Based Observations

AERONET is a well-established ground-based aerosol monitoring and characterization network, which provides standardized ground measurements on a regional and global scale (Holben et al., 1998). The AERONET sun photometers measure directly the AOD at various wavelengths, extending from 340 to 1640 nm (440, 670, 870, 940, and 1020 nm are standard) with an estimated uncertainty level of 0.01–0.02 (Holben et al., 2001). The solar-powered radiometers take measurements at eight spectral bands between 340 and 1020 nm every 10 s, with the high temporal frequency allowing for the screening of clouds. By considering scattering angles of 120° or more, the size distribution, phase function, and refraction indices of aerosols can be estimated. The AOD at a given site is reported every 15 min (Holben et al., 1998).

In this study, we have used the version 2.0 processed product, in which measurements during cloudy conditions are removed and a manual quality control is performed. There are more than 10 registered AERONET stations within the UAE, with only two having data records longer than five years: Masdar station in Abu Dhabi (23.105ºN, 53.755ºE), a coastal site, and Mezaira (24.442ºN, 54.617ºE), a station located deep in the inland desert close to the southern border (Figure 1). Measurements at these two contrasting sites are helpful to study the spatial variability of the aerosol loading in the country. Data from January 2012 to December
2019 for Masdar and from August 2007 to May 2018 for Mezaira are downloaded from AERONET’s website (https://aeronet.gsfc.nasa.gov), and subsequently used for analysis.

### 2.1.2. Satellite Observations

The CALIPSO mission is an ongoing collaboration effort within the framework of the American space agency, the National Aeronautic and Space Administration (NASA), and the French space agency, the National Center for Space Studies (Winker et al., 2003). The CALIPSO satellite was launched on April 28, 2006, and it has been acquiring global profiles of clouds and aerosols between latitudes 82°N and 82°S since then. It orbited as a part of the A-constellation satellites at an altitude of about 705 km until early 2018, which cross the equator at 1:30 and 13:30 local time, and have a 16-days orbit cycle with cross track errors of ±10 km (Winker et al., 2003). In February 2018, CALIPSO transitioned to the C-constellation satellites, reaching its final altitude of roughly 688 km in October 2018 (Braun et al., 2019). Such a change in altitude is unlikely to have an impact on the results presented in this work as (i) less 13% of the CALIPSO measurements considered here were collected from February 2018 to December 2019 and (ii) nearly all aerosols are in the bottom 8 km of the atmosphere, and therefore, the AOD estimates will be largely the same. The satellite carries three instruments: The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), which provides vertical profiles of aerosol and cloud-related variables, the target of this work; the Wide Field Camera (WFC); and the Imaging Infrared Radiometer (IIR) used to estimate the emissivity and size of the particles that form cirrus clouds. In the lower troposphere, CALIOP has a horizontal and vertical sampling resolution of 333 and 30 m, respectively, which are degraded to 180 m and 5 km in the stratosphere (Winker et al., 2003).

In this work, the AOD is read in directly from CALIPSO data, in particular from CAL_LID_L2_05kmA-Lay-Standard-V4-20 data product (variables: Column_Optical_Depth_Tropospheric_Aerosols_532 and Column_Optical_Depth_Tropospheric_Aerosols_1064). The quality metrics applied on these products include 1) Feature_Classification_Flags = 3 (Aerosol); 2) Number_Layers_Found ≥ 1; 3) ExtinctionQC_532 and ExtinctionQC_1064 = 0, 1; 4) Cloud-Aerosol Discrimination (CAD) score between −100 and −70; 5) Column_Optical_Depth_Tropospheric_Aerosols_Uncertainty_532 and Column_Optical_Depth_Tropospheric_Aerosols_Uncertainty_1064 < 99.9 km⁻¹. To analyze the aerosol extinction coefficient with respect to altitude, we used the CAL_LID_L2_05kmAPro-Standard-V4-20 data product. The aforementioned quality screening metrics are comparable to, and some even more conservative than, those employed in similar studies such as Winker et al. (2003), Campbell et al. (2012), and Toth et al. (2016). All the measurements discussed in the present study are taken in cloud free conditions (Feature_Classification_Flags = 3, Aerosol). Three parameters, namely the CAD score and uncertainty of optical depth, and the extinction quality flags (Ext_QC = 0,1) are used to assess the quality of the CALIPSO data. The standard CAD scores reported in the CALIPSO layer products range between −100 and 100. The sign of the CAD score indicates the feature type: positive values signify clouds, whereas negative values signify aerosols. The absolute value of the CAD score provides a confidence level for the classification. CALIPSO can effectively eliminate the interference of clouds to distinguish aerosols with a high degree of confidence by limiting the CAD score to the range −100 to −70, more conservative than that used in Winker et al. (2003), Campbell et al. (2012), and Toth et al. (2016), and the uncertainty of feature optical depth less than 99.9 km⁻¹ (Young et al., 2018). In addition to the CALIPSO layer and profile products, we have analyzed the Vertical Feature Mask (VFM) product (level 2, Standard Version 4–20) for aerosol sub-type identification. The version 4 VFM data product includes seven tropospheric aerosol subtypes, namely: 1) clean marine, 2) dust, 3) polluted continental/smoke, 4) clean continental, 5) polluted dust, 6) elevated smoke, and 7) dusty marine, defined in Kim et al. (2018). The CALIPSO data are downloaded from the Langley Atmospheric Science Data Center’s website (https://eosweb.larc.nasa.gov/). Further details regarding the comparison of CALIPSO AOD with that of AERONET are given in Section 3.

### 2.2. ERA-5 Reanalysis Data

In order to link the observed distribution of aerosols to the synoptic-scale circulation in the UAE, ERA-5 reanalysis data (Hersbach et al., 2020) are used. This product provides several surface/near-surface and 3D fields on an hourly basis from 1979 to present. The spatial resolution is 0.25⁰, or about 27 km in the meridional direction, and the temporal resolution is 1 h, the highest of the currently available reanalysis products.
The reanalysis data are downloaded from Copernicus’ website (https://climate.copernicus.eu/), for the domain 10ºN-40ºN and 30ºE-70ºE, which comprises the full Arabian Peninsula.

3. Methodology

To use CALIPSO AOD with confidence, we first compare it with in situ AOD observations at the two stations in the UAE. To do so, spatially and temporally coincident measurements of the sun photometers (AERONET) and CALIPSO are evaluated. As stated by (Bréon et al., 2011), there are two ways of intercomparing satellite and ground-based measurements. The first consists of averaging in time the sun photometer measurements so as to match the timestamp and spatial extent of the satellite swath within a specified radial distance from the ground site. In the second approach, the closest (in time and space) satellite retrieval coincident with the photometer observations is selected for analysis. In this study, we used the latter.

Furthermore, as the AOD measurements from CALIPSO and AERONET are at different wavelengths, they have to be processed so as to conduct a proper evaluation. According to Prasad et al. (2007), the AOD at two wavelengths, $\lambda_1$ and $\lambda_2$, can be expressed as

$$\left( \frac{\text{AOD}_{\lambda_1}}{\text{AOD}_{\lambda_2}} \right) = \left( \frac{\lambda_2}{\lambda_1} \right)^{-\alpha}$$

where $\alpha$ is the Angstrom exponent, a nondimensional parameter that expresses how AOD varies as a function of the wavelength (Bibi et al., 2015). Here, the AERONET-estimated AOD at 532 nm is computed using Equation 1, the measured AOD values at 500 nm, and the $\alpha$ for 440–870 nm.

While the ground measurements are point observations, there is a need to process the satellite data given its wider spatial and temporal extent. For this we need to average the satellite data in space and time. First, we averaged CALIPSO data in a 40 km radius of each AERONET station. The number CALIPSO overpasses in each month at the location of Masdar and Mezaira stations during daytime and nighttime are given in Table S1. Second, we have considered a time window of 30 min within each ground-based observation. Bréon et al. (2011) proposed thresholds of 50 km and 30 min for MODIS products, in line with those employed here. What is more, the 30 min window was found to be optimal for the two sites: although not statistically significant, a lower correlation, and higher Root-Mean-Square-Difference (RMSD) was obtained when the length of the time window was further increased. In other words, despite having a larger radius for the spatial averaging, the recommended 30 min temporal window is found appropriate for the set up considered here. A total of 24 data points out of the 111 CALIPSO overpasses over the Masdar station, and 33 data points out of the 108 overpasses over the Mezaira station, were available for comparison with the AERONET measurements.

The method described above was used in several studies over different regions. For instance, Omar et al. (2013) compared the AOD retrieved from CALIPSO with that measured at a coincident set of 149 AERONET stations throughout the world from 2006 to 2010. They found that CALIPSO’s 550 nm (visible) AOD is lower than that of AERONET in particular for AOD < 0.1, with a relative difference in the median of 25% for AOD > 0.1. These differences have been attributed to cloud contamination (CALIPSO observations indicate the presence of clouds in more than 45% of the pixels that AERONET classifies as clear), measurement uncertainty, and spatial inhomogeneity. A similar conclusion was reached by Ogunjobi and Awoleye (2019) for six sites in West Africa. On the other hand, Bibi et al. (2015) reported that in a study over the Indo-Gangetic Plains, the CALIPSO AOD values were greater than their AERONET counterparts in almost all seasons. C. Liu et al. (2014) compared the two datasets over China from June 2006 to December 2012, reporting a correlation of more than 50% in the highly industrialized northern and northeastern regions, and lower scores in the southern and eastern regions. In line with Omar et al. (2013), the authors reported higher values of AOD from AERONET compared to CALIPSO, and attributed this to cloud contamination from differences in the instrument viewing angle. Another important conclusion of their study was the limited ability of CALIPSO to collect data close to the ground during daytime hours, which arises from the low signal-to-noise ratio (SNR) due to the high solar elevation angle.
Figure 2 shows a scatter plot of the observed AOD from AERONET and CALIPSO at the location of the two stations considered (coastal Masdar and inland desert Mezaira) for the wavelengths of 532 and 1020 nm. It is important to note that, while in the top panels, the estimated AOD from AERONET and CALIPSO at a wavelength of 532 nm is compared, there is a wavelength discrepancy in the bottom panels (1020 nm in the former and 1064 nm in the latter). Unfortunately, this mismatch cannot be corrected using Equation 1, as the Angstrom exponent is not known for such wavelengths. The two AOD estimates are generally in agreement, with correlations of 0.4–0.6 at Masdar and 0.6–0.8 at Mezaira, and RMSDs that do not exceed 0.2 at both sites. This agreement is deemed to be good given that the number of samples is relatively small (just 24 for Masdar and 33 for Mezaira), and that the comparison is between measurements by a satellite covering a swath of 40 km, and in situ observations at one location inside that region. The agreement between the two datasets is comparable to that reported by other authors, such as Bibi et al. (2015). For four locations in India and Pakistan, the authors reported correlations between the two datasets in the range 0.2 and 0.5. Correlation coefficients between 0.5 and 0.9 have been also found by Ogunjobi and Awoleye (2019) for six stations in West Africa. RMSDs less than 0.2 have also been obtained by Bibi et al. (2015) and Omar et al. (2013) (the latter targeted 149 AERONET stations, the majority of which were in the tropics and subtropics).

For both stations, the correlations and RMSDs are lower for the visible channel compared to the infrared channel. This can be explained by the reduced SNR during the day due to the solar background that affects the active lidar remote sensing from CALIPSO (Rogers et al., 2014). The higher correlation coefficients for
Mezaira may arise from the proximity of the station to the CALIPSO track, Figure 1, which helps in acquiring more representative values of AOD compared to the ground-based estimates. It is interesting to note that AERONET AOD at Masdar is larger than that estimated by CALIPSO at both wavelengths, consistent with Omar et al. (2013), with the opposite being true for Mezaira. A possible explanation is that the Masdar station is located close to the Arabian Gulf (Figure 1), where sea-salt aerosols, which have a reduced AOD compared to the dust ubiquitous in the inland desert (Al-Salihi, 2018), are likely to be present. On the other hand, the dustier atmosphere in the Rub’ Al Khali desert may contaminate the CALIPSO-estimated AOD, leading to higher values than those measured in situ. In particular, it is possible that the presence of high-altitude dust layers at Mezaira, as reported at rural sites in the UAE (Filioglou et al., 2020), and to which CALIPSO measurements are known to be more sensitive (Winker et al., 2003), may lead to higher satellite-derived dust loadings. For example, the top outlier in Figure 2d is found to be associated with an elevated dust layer over Mezaira on July 2, 2012 (not shown). Such dust layers are more likely at inland sites where the boundary layer is deeper (Filioglou et al., 2020; Reid et al., 2008), than at coastal sites like Masdar where boundary layer depths are generally below 2 km (Reid et al., 2008; Temimi et al., 2020). The deeper boundary layers inland are caused not only by the higher surface temperatures, but also the increased surface roughness, which leads to a slowdown of the near-surface wind and consequently low-level wind convergence and vertical ascent (Nelli et al., 2020b). Other explanations for these mismatches, as highlighted in (Omar et al., 2013), include differences in the instrument view angle, inhomogeneities in the target region and column, CALIPSO retrieval errors, and detection limits.

In summary, despite the aforementioned differences, the CALIPSO data can be considered to provide a good estimate of the aerosol loading at the locations of the two stations, Masdar and Mezaira. Thus, together with the AERONET measurements, it is suitable for a discussion of the variability of the AOD in the UAE on different temporal scales.

### 4. Synoptic-Scale Environment Over the Region

In this section, the synoptic-scale atmospheric conditions in the Arabian Gulf region are outlined using ERA-5 data detailed in Section 2.2.3 for the period 2007–2019, when AERONET measurements are available for analysis. The seasonal mean 10-m horizontal wind vector, 2-m temperature and specific humidity, and mean sea-level pressure at 10 UTC (14 local time, LT, in the UAE) and 22 UTC (02 LT) are given in Figures 3 and 4, respectively. These hours correspond to the daytime and nighttime overpass times of CALIPSO over the UAE, where the intercomparison between the satellite-derived and ground-based estimation of AOD is performed.

The daytime conditions (Figure 3) show the prevailing sea-breeze circulation, which has a higher amplitude in the summer season when the land-sea temperature gradient is at its maximum. In this season, there is an approximate 10 C difference in air temperature between the very hot land, where daytime highs are mostly in the range 40–45 °C, and the much cooler Arabian Gulf, where air temperatures peak at just 30–35 °C. Daytime highs in the summer exceed 40 °C in nearly all landmasses, with the highest seasonal mean daily maximum temperatures, in excess of 45 °C, occurring over southeastern parts of Iraq and Kuwait, to the northwest of the Arabian Gulf, due to the advection of very hot air by the Shamal winds, as also noted by Al Senafi and Anis (2015) and Yu et al. (2016). In winter, the referred temperature difference is typically below 5 °C. As a result of the strong heating of the surface by the sun, the evaporation in the Arabian Gulf and Sea of Oman is very large in particular in the warmer months, with specific humidities in excess of 20 g kg⁻¹ that are advected inland by the sea-breeze, in line with P. Xue and Eltahir (2015). While in the summer a thermal low is the predominant near-surface circulation feature in the region, in winter the Siberian high extends westwards into Iran and western Asia (Seager et al., 2003), bringing cooler and drier air into the area. In particular, over the high terrain, wintertime highs are generally below 10 °C, with specific humidities not exceeding 5 g kg⁻¹.

The nighttime conditions (Figure 4) reveal a much weaker and less-well defined land breeze circulation, with speeds generally below 2 m s⁻¹. The land breeze is slightly stronger in the cold season, owing to a larger temperature difference between the cooler land, where strong radiative cooling leads to nighttime temperatures below 15 °C nearly everywhere, and a milder Arabian Gulf and Sea of Oman, where the air
temperatures generally exceed 15–20 °C. A comparison of Figure 3 with 4 shows the inland propagation of the moister maritime air, in particular in the summer, when the land-sea humidity gradient is more significant.

The maximum wind speeds in the UAE, of about 5 m s⁻¹, occur in the summer late-afternoons, in response to a more vigorous sea-breeze circulation, whereas the weaker land-sea breeze and associated offshore winds that oppose the background flow lead to more quiescent conditions at night (~0–2 m s⁻¹), in particular in coastal regions (Figure 4). The presence of the Zagros mountains in Iran to the east of the UAE leads to locally enhanced slope circulations (Najafi et al., 2017) as well as an enhanced sea-breeze circulation, in particular in the summer months.

A further inspection of Figures 3 and 4 reveals that, in the summer, the southwesterly winds associated with the Asian summer monsoon, turning southeasterly over the Sea of Oman, converge with the north to northwesterly Shamal winds, and with the northern Levar over southeastern parts of Iran. This has been noted by Rashki et al. (2019), and this can lead to the accumulation of large amounts of dust aerosols in the region.

The background atmospheric conditions in the UAE described in the above paragraphs will help understand the spatial and temporal variability of aerosols in the country discussed in the following sections. For example, marine aerosols are advected inland during the day by the sea-breeze circulation, while the weaker wind speeds and more quiescent conditions at night will likely favor reduced amounts of lifted dust in the atmosphere.
5. Climatology of Atmospheric Aerosols Over the UAE

5.1. Aerosol Subtypes

In Figures 5 and 6, the prevailing aerosol subtypes for each season, for the whole of the UAE and in a 40 km-radius around Masdar and Mezaira are given for daytime and nighttime, respectively. Shown is the frequency of occurrence of a given aerosol subtype with respect to the total number of profiles collected, the latter given in Table 1. Due to the low number of available profiles, nighttime profiles are not given for Masdar. The three dominant aerosol subtypes are “dust” (red curve), “polluted dust” (blue curve), and “polluted continental” (green curve). As described in Kim et al. (2018), “polluted dust” refers to a mixture of dust with biomass burning and urban pollution, even though a mixture of dust with marine aerosols is also frequently classified as “polluted dust.” On the other hand, and as detailed in Barnaba and Gobbi (2004), “polluted continental” represents aerosols from industrialized countries from both anthropogenic and biogenic sources such as fossil fuel combustion and industrial activities.

Dust is clearly the predominant aerosol subtype in the region, in particular in the summer season (Figures 5 and 6), when dust storms occur more frequently in the UAE (Aldababseh & Temimi, 2017; Yu et al., 2015). On the other hand, polluted continental is only seen in the cold season, below 2 km altitude, and with a percentage of occurrence generally less than ~10%. Given that these fine aerosol particles have their origin in industrialized nations, it is not surprising that they are more prevalent in winter, when the background northwesterly winds are stronger and mid-latitude baroclinic systems regularly affect the region (Naizghi & Ouarda, 2016). The low-level flow may advect these aerosols from the big cities around the Arabian Gulf downstream into the UAE (Figures 3 and 4). Polluted dust is also more frequently observed in the country in the winter and autumn seasons, and is also likely to be carried by the background winds. This analysis
is in line with that performed by Al-Salihi (2018) over Baghdad in Iraq, and by Filioglou et al. (2020), who analyzed the properties of aerosols in the UAE at Al Dhaid, a rural site in the Dubai emirate.

The warmer and more convective environment in the summer season transports the aerosols up to 5–6 km above the surface, whereas the colder temperatures and more stable conditions in winter facilitate trapping of the aerosols in the lowest 2 km (Figures 5 and 6). The peak in aerosol amount in Figures 5 and 6 is in the bottom 1–2 km, near the top of the boundary layer (Filioglou et al., 2020). The secondary peak at ∼3–4 km, of a higher magnitude in spring and summer, suggests the presence of another aerosol layer, which is more pronounced at Mezaira, where the environment is dustier, as seen in Figure 6. Figure 5 also highlights the gradual increase in the height of the daytime boundary layer, with a depth of 4 km in winter, rising to 5 km in spring/autumn, and 6 km in summer.

The main difference between the daytime and nighttime analyses is the increased amount of polluted dust during daytime (and, to a lesser extent, polluted continental) and slightly reduced amount of dust mainly in the autumn and winter seasons at night. As dust can be generated in situ, the weaker wind speeds at night (compare Figure 3 to 4) mean less amounts of dust will be in the air, while the concentration of the other two aerosols that are advected into the region builds up in the more quiescent conditions after sunset. It is interesting to note that the aerosol subtype distribution in Mezaira is roughly representative of that of the
country as a whole, while at Masdar the environment is less dusty and contains fewer aerosols, in line with Figure 5.

5.2. The Aerosol Optical Depth

The aerosol loading in the region is higher in the summer during daytime (Figures 5 and 6) in response to intensified local-scale circulations, which can lift more particles from the surface and lead to dustier conditions (Beegum et al., 2018; Bou Karam Francis et al., 2017; Yu et al., 2015, 2016). This is consistent with the combination of drier conditions and stronger near-surface winds during this season, as seen in Figure 3. Dust lifting also depends on the availability of deflectable materials and on the soil properties (Laurent et al., 2008). Moreover, as pointed out by Rashki et al. (2019), and also seen in Figure 3, the convergence of the north to northwesterly Shamal winds, with the northerly Levar winds, and the southeasterly winds associated with the Asian summer monsoon, may suppress the transport of aerosols out of the region, leading to locally higher values of AOD.

Figure 7 gives the mean and standard deviation of the AOD from CALIPSO for daytime/nighttime and for the wavelengths of 532 and 1064 nm. The spatial pattern of the AOD for the visible (532 nm) wavelength resembles that for the infrared (1064 nm) wavelength, but with larger magnitudes. This is consistent with the fact that most aerosols have a more significant impact in the radiative transfer in the visible band of the electromagnetic spectrum (Al-Salihi, 2018). In addition, the diurnal peak in AOD is found in the local late afternoon/evening hours, after the daytime circulations lift the particles higher up in the atmosphere, when the boundary layer is deeper and more convective in nature (Temimi et al., 2020). This can also facilitate the detection of atmospheric aerosols by CALIPSO, which is more sensitive to higher-altitude aerosols (Winker et al., 2003).

Even though the AOD is generally higher during daytime over the UAE, its spatial distribution is not as uniform as at night (Figure 7), with two regions of abnormally low values: (i) extreme western UAE, (ii) roughly

| Table 1 |
| Number of CALIPSO Profiles for the Period 2006–2019 Over the Whole UAE, a 40 km Radius Zone Around Mezaira and Masdar for Winter (DJF), Spring (MAM), Summer (JJA), and Autumn (SON) Seasons During Daytime and Nighttime |

| Location | DJF  | MAM  | JJA  | SON  |
|----------|------|------|------|------|
| UAE      | Daytime | 2435 | 2363 | 2061 | 2596 |
|          | Nighttime | 5885 | 5594 | 4625 | 6972 |
| Mezaira  | Daytime | 219  | 206  | 246  | 258  |
|          | Nighttime | 815  | 714  | 575  | 745  |
| Masdar   | Daytime | 234  | 233  | 181  | 305  |
|          | Nighttime | 8    | 29   | 20   | 59   |
circular area in central parts of the country, to the southwest of Masdar. Figure 3 shows that, and mostly in the summer season, the sea-breeze penetrates further inland and is stronger on the western side of the country. The lower AOD observations here can be possibly explained by the increased advection of marine aerosols (e.g., sea salt) into the region, which have lower AOD compared to dust particles (Al-Salihi, 2018). The seasonal mean plots, Figure S1, confirm that lower AOD values in extreme western UAE are more pronounced in the summer, while in spring the opposite is true, when the AOD is lower around Masdar and to the northeast where the sea-breeze is stronger, as seen in Figure 3. The localized minimum in central parts of the country largely overlaps with a region of drier atmospheric conditions (Figures 3 and 4). As noted by Ogunjobi and Awoleye (2019), in a more moist environment, the AOD is likely to be larger due to the condensation of water vapor on the aerosols, which leads to an increase in their size, with the opposite in drier conditions. This feature is present in all seasons, but is less pronounced in spring (Figure S1).

The spatial patterns of the standard deviation maps are broadly similar to those of the mean given in the top row, but with a lower magnitude typically of 0.1 (roughly 30%–40%). The large amplitude of σ can be explained by the significant interannual variability of dust events in the region, as reported, for example, by Aldababseh and Temimi (2017) and Yu et al. (2015).

6. Annual, Diurnal, Seasonal, and Interannual Variability of AOD

In this section, the annual, diurnal, seasonal, and interannual variability in AOD over the UAE are assessed, using a combination of satellite-derived (CALIPSO) and ground-based estimated (AERONET) observations.

6.1. Annual Variability of Extinction Coefficient

Figure 8 shows the extinction coefficient in the bottom 6 km from CALIPSO, averaged over the UAE for daytime and nighttime during 2006–2019, and the two wavelengths. As highlighted in the previous sections, the results for $\lambda = 532$ nm and $\lambda = 1064$ nm resemble each other, with the lower values of AOD for the latter consistent with Equation 1 and Al-Salihi (2018).

The peak in aerosol loading is in the summer, more precisely in July-August (Figure 8), when the extinction coefficient exceeds 0.2 km$^{-1}$ in the lowest 2–3 km of the atmosphere. The secondary peak seen in February (mid-winter) is associated with dust storms generated over the Arabian Peninsula by southward propagating baroclinic systems from the mid-latitudes (Abdi Vishkaee et al., 2012; Kaskaoutis et al., 2019; Notaro...
et al., 2013). As highlighted in Yu et al. (2016), even though the winter Shamal is stronger than its summer counterpart, with near-surface wind speeds in the Arabian Gulf of up to 20 m s⁻¹, the summer Shamal occurs more frequently, and is closely related to dust concentrations in the Gulf region. This, together with the more humid and colder conditions in the winter season, explains why the extinction values are higher in the summer months, and extend deeper in the vertical. The deeper aerosol layer in the warmer months is also consistent with the frequency of occurrence profiles given in Figures 5 and 6.

A comparison of the daytime and nighttime results shows that the peaks in the latter are at lower heights and generally broader. This is consistent with the shallower nocturnal boundary layer (Temimi et al., 2020), which acts as a trap of the dust closer to the surface, leading to a reduction of the horizontal visibility and dustier conditions (Abdi Vishkaee et al., 2012; Reid et al., 2008) at very low levels. Similar results are obtained at the locations of Masdar and Mezaira (Figure S2).

6.2. Diurnal and Seasonal Variability of AOD

Figure 9 shows the seasonal variability of the AOD from AERONET at the location of Masdar and Mezaira, from 03 UTC (07 LT) to 13 UTC (17 LT), for the two wavelengths. The AOD values at the two stations are the highest in the summer and the lowest in winter, with intermediate values in the transition seasons (both in spring is generally dustier than autumn). On the other hand, the secondary peak in AOD in February seen in Figure 8 is not reflected in the winter mean values. Even though it features in the CALIPSO data for the closest grid-point to both Masdar and Mezaira (Figure S2), the fact that the AOD is lower in December-January and March-April, means that it will be smoothed out in the 3-months average. Figure 9 also shows that spring is dustier than autumn at both the sites. This is in line with Figures 3 and 4, which show windier (as well as lower sea-level pressures) in the former, which are more conducive to the occurrence of dust events (Yu et al., 2015, 2016). Moreover, the higher AOD values in spring may arise from dust aerosols being picked up by south-westerly winds from the arid and semi-arid parts of the region (Basha et al., 2015). As expected,
the standard deviation is larger when the mean AOD is higher, ranging from about 0.1 in the colder months to 0.2 in the summer season, roughly half of the mean value.

The AOD remains nearly constant throughout the day, although in Mezaira, the values increase slightly from 08 UTC (12 LT) to 11–12 UTC (15–16 LT), especially during summer. This suggests the occurrence of local dust emissions at this time of the day triggered by the arrival of the sea-breeze at the site (Figure 3) and/or by downdrafts from convective events that can develop near this site in the warm season (Wehbe et al., 2020). The small increase in AOD in the early morning hours (≈8–9 LT) at both stations arise from local dust emissions by stronger winds triggered by the downward mixing of momentum of the nighttime low-level jet, which arises from the strong land-sea temperature contrast (Giannakopoulou & Toumi, 2012), to the surface, when turbulence increases and the boundary layer deepens after sunrise (Washington et al., 2006). The fact that this variability is more pronounced in the warm season is consistent with the fact that the referred low-level jet is stronger in the summer (Bou Karam Francis et al., 2017).

6.3. Interannual Variability of AOD

In this subsection, the interannual variability of the AOD averaged over the UAE as given by CALIPSO is investigated. Figure 10 shows the yearly values for daytime, nighttime, and daytime-nighttime combined for the visible and infrared wavelengths from 2006 to 2019. The higher daytime values have been discussed in Section 6.2, and they can be attributed to the stronger winds and a deeper and more convective boundary layer.
A clear, albeit small, decreasing trend can be seen from 2009 onwards, in particular in the daytime AOD, which goes from being $\sim 0.15$ higher than the nighttime estimates in 2009, to being comparable in 2018, and then slightly lower by $\sim 0.5$ in 2019. A similar trend has been noted by Aldababseh and Temimi (2017) for Abu Dhabi and Dubai. A possible explanation is the increasing trend in precipitation in the same period, seen in panel (c), as rainfall is known to wash-out aerosols leaving the atmosphere cleaner (Lau & Kim, 2006). In addition, changes in land use and land cover in the UAE, noted for example, by Aldababseh et al. (2018), can also explain the decreasing trend in AOD. While urbanization may lead to an increase in pollution and hence in the AOD values (R. Xue et al., 2019), it will also reduce the potential for dust emission. As dust is the prevailing aerosol subtype in the country (Figures 5 and 6), and provided that the increase in AOD due to the pollution does not outweigh the decrease due to the reduced amounts of dust, less dust means overall lower AOD values, in line with what is seen in Figures 10a and 10b. Another factor that may play a role in the decreasing AOD values is the cloud seeding activities that have been conducted over the UAE in the last two decades (Al Mazroui & Farrah, 2017), although it is hard to disentangle the climate change signal from that of natural variability.

7. Conclusions

Given the crucial role aerosols play in the atmospheric radiation budget and dynamics (Azua-Bustos et al., 2019; Forkel et al., 2012) and their impacts on human health (Boersma et al., 2008), it is imperative to understand their spatial and temporal variability, in particular, in source regions like the UAE. Previous studies focused either on individual aerosol-related events (Basha et al., 2015), or on the regional synoptic conditions (Eager et al., 2008), without linking them to the aerosol distribution. In this article, the referred two aspects are discussed together, with the spatial and temporal distribution of aerosols in the UAE analyzed in detail. The AOD measured by the CALIPSO satellite is first evaluated against in situ measurements by the AERONET sun photometers at the two sites in the UAE: the coastal Masdar and the inland Mezaira. The two measurements are found to be in reasonable agreement, with correlations between 0.4 and 0.8 and RMSDs below 0.2. The satellite-derived AOD is generally smaller than that measured in situ at Masdar, likely because of the potential influence of marine aerosols that have a lower AOD compared to dust. The opposite is true at Mezaira, possibly due to the presence of high-altitude dust layers to which CALIPSO is sensitive. The higher scores in the near-infrared band ($\lambda = 1064$ nm) compared to the visible band ($\lambda = 532$ nm) can be explained by the lower SNR in CALIPSO during the day, due to the solar background interference with the lidar measurements, a finding highlighted by Rogers et al. (2014). The satellite product is subsequently used for a general study of the variability of aerosols in the UAE on diurnal, monthly, seasonal, and interannual time-scales.

The dominant aerosol subtype in the UAE is dust, even though, and mostly in the cold season, polluted dust (i.e., dust mixed with biomass burning and urban pollution) and polluted continental (i.e., aerosols arising from biogenic/anthropogenic sources in industrialized nations) are also present, likely advected southward by the stronger background winds from countries around the Arabian Gulf. An analysis of the vertical profiles reveals two main layers, one just above the surface in the bottom 2 km, likely associated with the diurnal variability of the boundary layer, and another between 2 and 6 km.

We found that AOD varies seasonally, being higher in summer and spring. A secondary peak in the AOD is observed in February, and is likely driven by dust events triggered by the strong winds associated with mid-latitude baroclinic systems. While the AOD, a column-integrated quantity, is nearly the same during daytime and nighttime, there are small variations, in particular in the early morning in association with the
augmented vertical mixing that brings the higher momentum winds from the nighttime low-level-jet down to the surface, according to the explanation proposed by Washington et al. (2006) and Bou Karam Francis et al. (2017). At Mezaira around noon and early afternoon, the AOD increases possibly from the arrival of the sea-breeze and occurrence of downdrafts from cloud development in summer and the associated increase in the amount of dust in the column. Finally, the UAE-averaged AOD has been decreasing from 2009 onwards, roughly when the annual accumulated precipitation started its positive trend despite the significant interannual variability. A possible explanation is that aerosols may be washed out by the rainfall, although recent changes in land use may also play a role.

The findings of this study highlight the quasi-permanent presence of dust aerosols over the UAE and the need for dust aerosols to be accounted for in climate projections as well as in meteorological and air-quality forecasts. Future studies may focus on an extension of this work to cover the entire Arabian Peninsula and Iran, to address the regional atmospheric composition and investigate the links to synoptic-scale patterns in the atmospheric circulation. Numerical simulations of aerosols' cycle in the region would also help to further the current understanding of their spatial distribution and to accurately assess their impacts.

Data Availability Statement

Data used in the present analysis are available online (https://kudrive.ku.ac/ne-no-shib/index.php/s/Fw8eET2RTmpuQGg).

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