Total cloud cover climatology over the United Arab Emirates

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Cloud climatologies are of great importance in the study of cloud dynamics and interactions with land, oceans and atmosphere. This study analyzes the climatology of Total Cloud Cover (TCC) over the United Arab Emirates (UAE). Monthly mean TCC data between 1984 and 2009 from ground observations at six UAE airport stations and the satellite-based (CLARA A2) product are utilized. The hourly ground observations are first filtered to match the overpass times of CLARA-A2 satellites over the UAE. Comparison between the datasets reveals higher TCC reports by CLARA-A2. These are attributed to several factors, such as the underestimation of TCC by human observers and the region's aerosol loading, surface albedo and emissivity, which impact the quality of remote sensing retrievals. Satellites utilized for CLARA-A2 are known to have undergone changes in their numbers and orbits over the years, prompting an investigation of its homogeneity. Change points are found to occur in 1991 and 1998, related to increased satellite measurements and sensor changes, respectively. Further investigations of the homogeneity of means and variances before and after the change points are also conducted, resulting in confirmation of the inhomogeneity induced by artifacts. Monthly means of hourly ground observations are then used for analysis of TCC climatology over the six stations. Fujairah has the highest TCC on average, due to its proximity to the Hajar mountains and the Oman gulf. Most of the stations exhibit significant decreasing trends, in addition to a change point occurring in 1998. This is theorized to be related to the El Niño Southern Oscillation phase change occurring in the same period. The potential teleconnection is explored further through testing for correlations of TCC with the Oceanic Niño Index, with results showing a strong link in the fall–winter seasons.

KEYWORDS
arid region, climatology, cloud cover, desert, ENSO, remote sensing, teleconnection

1 | INTRODUCTION

Clouds play an important role in the planet's energy balance and climate (Liou, 1986; Ramanathan et al., 1989; Chahine, 1992; Calbó and Sanchez-Lorenzo, 2009). Establishing records of cloud characteristics is of critical importance to better understand their dynamics (Warren et al., 2007). Surface-based observations have been used to develop such records. However, cloud characteristics that are derived from these observations are constrained by the spatial and temporal coverage provided. Alternatively, a substantial satellite-based cloud record has been collected for decades. Satellite instruments provide relatively shorter records though when compared to ground-based stations. Passive sensors can be associated with some uncertainties related to observation geometry challenges (Norris, 2000; Warren and Hahn, 2002). Additionally, orbital drifts of satellites have impacts on measurement records; one such effect of the different equatorial crossing times caused by drifts is varying illumination, which influences measurements taken by
sensors (Pinzón et al., 2014). The changing of equatorial crossing time also results in measurements taken at different temporal points of the diurnal cycle, causing shifts in the long-term record. Changes in sensors and their respective calibrations can also lead to artifacts in measurements (Liu et al., 2004). Several studies have found large discrepancies in cloud cover reports when comparing sparse ground measurements to satellite data (McKenzie et al., 1998; Wu et al., 2014).

On the meso- and synoptic scales, cloud cover characteristics are governed by the balance of heat and moisture in the atmosphere, land and oceans (Prasad et al., 2015). Locally, land use changes, specifically urbanization, are reported to have effects on microscale atmospheric circulations (Rabin et al., 1990; Wen et al., 2012; Zhong et al., 2017). Urbanization effects, including anthropogenic aerosols and the urban heat island (UHI) effect, are complex in nature and differ by location, leading to varying effects on microclimate and, consequently, clouds (Collier, 2006). In desert regions, clouds are sporadic and intermittent in nature, causing significant uncertainty for their studies and their parametrization in climate models.

The Arabian Peninsula, a subtropical desert with hyper-arid climate (Böer, 1997; Chaouch et al., 2017; Wehbe et al., 2017; Wehbe et al., 2018; Weston et al., 2018), is located in a transitory zone in between two circulations (the Mediterranean and Monsoon). The descending air on the poleward side of the Hadley cell produces a belt of fairly permanent high pressure over the Peninsula, leading to suppressed convection and lower amounts of clouds in comparison to the tropics (at the ascending branch of the Hadley cell) and higher latitudes (Al Mandoos, 2005). The region experiences regular dust storm events (Gherboudj and Ghedira, 2016), with atmospheric stability affected by the position and strength of the Sub-Tropical Jetstream (STJ) (Hasanean, 2004; Shalaby et al., 2015). The United Arab Emirates (UAE) lies in the south-east region of the Peninsula (see Figure 1). A number of studies have been conducted to establish connections between meteorological variables in the Arabian Peninsula, and the UAE specifically, and the El Niño Southern Oscillation (ENSO) (Ouarda et al., 2014; Chandran et al., 2015; Aldababseh and Temimi, 2017; Abid et al., 2018).

Although numerous studies have been conducted on global and regional scales to analyze cloud cover climatologies and trends (Henderson-Sellers, 1986, 1989; Mokhov and Schlesinger, 1994; Kaiser, 1998, 2000; Warren and Hahn, 2002; Milewska, 2004; Roy and Balling, 2005; Endo and Yasunari, 2006; Calbó and Sanchez-Lorenzo, 2009; Jin et al., 2009), there is a significant gap in the literature on the climatology of clouds over deserts—despite the crucial role they play in understanding the link between aridity and cloud formation. The aim of this study is to address the knowledge gap in total cloud cover (TCC) climatology over

![Map of the United Arab Emirates showing elevations from GTOPO30 (DAAC, 2004) and locations of airport observation stations](image-url)
the Arabian Peninsula, specifically over the UAE. The discrepancies in reports of ground observations and satellite measurements are explored and discussed, with attention given to the homogeneity assessment of the satellite record. The links of TCC spatial differences with land cover conditions are discussed, in addition to investigation of a possible ENSO teleconnection.

2 DATA AND METHODOLOGY

This study analyzes monthly averages of TCC from 1984 to 2009. With cloud trends being highly sensitive to interannual and decadal variability, it is important to note the time period that is being considered for climatological studies. Quantitative surface observations of hourly TCC for six airport stations in the UAE (location details provided in Figure 1 and Table 1) are obtained from the UAE National Center of Meteorology (NCM). With the exception of Al Ain, all stations are coastal. The Fujairah and Al Ain stations are in proximity to the Al Hajar mountain chain. The areas encompassing the remaining stations are dominated by urban and flat terrains. The observations are taken by trained observers at airport stations across the UAE and reported in oktas following World Meteorological Organization synoptic code. It should be noted that the use of human observers can result in inconsistencies of report over periods of time. The observations, originally reported in oktas, are converted into percentages; one okta is equivalent to 12.5%. The hourly surface observations are then aggregated to monthly averages. The monthly averages are included on the basis that almost a complete dataset of hourly reports is available; that is, the month is excluded if more than 1% of the hourly reports are missing. These monthly averages using all 24 daily observations will be referred to as “unfiltered” ground observations.

Information on TCC over the UAE are also obtained from CLARA A2, the second edition of the satellite-derived climate data record CLARA (Karlsson et al., 2017b). The data record is produced by the European Organisation for the Exploitation of Meteorological Satellites Climate Monitoring Satellite Application Facility (CM SAF) project. Its temporal coverage extends from January 1982 to December 2015. More details on the CLARA-A2 dataset are given by Karlsson et al. (2017a). Reduced performance of the cloud screening method used for CLARA-A2 has been reported over dry and generally cloud-free areas. For this study, the monthly average TCC at 0.25° × 0.25° resolution is utilized. Six grid cells of 0.25° × 0.25° are calculated using linear interpolation such that their center corresponds to the airport stations’ locations. Horizontal visibility can be used to match station observations with satellite cells (Kotarba, 2015). Based on the work of Aldababseh and Temimi (2017), average visibility ranges from 8.7 to 10.6 km for the UAE airport stations, which would mean that ground observations are reported within the radius of the CLARA-A2 cells (approximately 11.5 km).

For the purpose of comparing with CLARA-A2, the hourly ground observations are filtered such that only those corresponding to the overpass times of the Advanced Very High Resolution Radiometer (AVHRR) sensors over the UAE are included. This is done to account for the varying number of National Oceanic and Atmospheric Administration (NOAA) and Meteorological Operation satellites used over the study period and the orbital drift of each of these satellites (Karlsson et al., 2017b), which lead to varying observation times and should be accounted for in the comparison due to the region exhibiting diurnal variability of TCC (Pfeifroth et al., 2012; Foster and Heidinger, 2013). This version of the ground observations record will be referred to as “filtered.” It should be noted here that the difference in TCC reports, that is, oktas for ground observations and percentages for CLARA-A2, should be a consideration when conducting comparisons.

The significance of trends is tested using the modified Mann Kendall test, which eliminates the effect of serial correlation in the traditional Mann Kendall test (Yue and Wang, 2004). The true magnitudes of the slopes of the data are estimated using the Theil-Sen’s estimator (Yue et al., 2002), which has been applied in several studies of hydro-meteorological variables (Dinpashoh et al., 2011; Jhajharia et al., 2014; Ouarda et al., 2014).

Homogeneity assessments of the data are conducted, through the detection of breaks (i.e., change points) in the data series and the study of mean and variance homogeneity between existing breaks. The Pettitt test, which has been used for studying homogeneity of hydro-meteorological datasets (Karabörk et al., 2007; Hakuba et al., 2013; Xie

| Airport         | Start Date | Unfiltered Ground Mean | SD   | Filtered Ground Mean | SD   | CLARA Mean | SD    |
|-----------------|------------|------------------------|------|----------------------|------|------------|-------|
| Al Ain          | Jan 1994   | 14.98                  | 8.91 | 19.23                | 11.16| 24.36      | 5.53  |
| Abu Dhabi       | Jan 1982   | 13.65                  | 8.78 | 17.16                | 11.09| 23.05      | 4.99  |
| Dubai           | Jan 1979   | 14.57                  | 10.09| 18.30                | 12.56| 24.16      | 6.51  |
| Sharjah         | Jan 1979   | 13.14                  | 9.59 | 16.55                | 11.88| 24.31      | 5.61  |
| Ras Al Khaimah  | Jan 1979   | 13.58                  | 10.00| 17.19                | 12.48| 24.01      | 5.05  |
| Fujairah        | Jan 1988   | 16.64                  | 9.25 | 20.25                | 11.31| 26.75      | 3.57  |
et al., 2014), is applied to detect change points. The graphical cumulative sum (CUSUM) change point analysis technique is also used (Kokoszka and Leipus, 1998; Ouarda et al., 2014). The homogeneity of means and variances are then assessed using the Student’s t test (Ouarda et al., 2014) and Levine’s test (Levene, 1960), respectively.

The record of the Oceanic Niño Index (ONI) values is obtained from the NOAA Climate Prediction Center (CPC). The ONI is calculated by averaging sea surface temperature anomalies in the Niño-3.4 region (Null, 2011). For this study, the 3-month running means of the anomalies are used and compared with the unfiltered ground observations. The agreement between TCC and ONI is assessed using the non-parametric Spearman’s rank correlation coefficients (Andrade Jr and Sellers, 1988; Zar, 1972).

3 | COMPARISON OF GROUND AND SATELLITE TCC REPORTS

In this section, filtered ground observations are used for comparison with the CLARA-A2 measurements over the six stations. Time series of the monthly mean filtered TCC ground observations and CLARA-A2 measurements over the six UAE airports are displayed in Figure 2, with summarized statistics in Table 1. The average TCC values from filtered ground stations and from CLARA-A2 are 18 and 24%, respectively.

A possible explanation for the discrepancies between ground and CLARA-A2 datasets could be the uncertainty in reporting TCC between day and night for both human observers and satellite sensors (Karlsson et al., 2015). Human observations of clouds are hindered at night due to reduced illumination (Hahn et al., 1995). To examine this, the day and night TCC reports are obtained separately from the CLARA-A2 product. The filtered TCC ground observations are averaged and separated into daytime and nighttime. The time series of both ground and CLARA-A2 datasets are averaged over all six stations, with the histograms of the results shown in Figure 3. During the day, ground observations in general report higher TCC than CLARA-A2 by 10–20% for TCC ranges below 50%, which is within the uncertainty range of ground observations. It is possible that this is due to ground reports of 1 okta, that is, 12.5%, which might have different corresponding reports in CLARA-A2. The next noticeable difference is for reports in the 50–70% range, which are higher for CLARA-A2 by up to 16 occurrences. At night, ground observation frequencies are almost double those of CLARA-A2 in the 0–10% range. For frequencies higher than 30%, CLARA’s reports are higher than ground, reaching up to 40 occurrences more in the 30–40% range. The higher frequencies at low TCC ranges by ground observers suggest an underestimation of TCC by CLARA-A2 during night time.

It is possible that increased aerosols could obscure ground observations of very thin middle and high clouds,

![FIGURE 2](image-url)
which would result in lower reported TCC (Warren et al., 2007). Increased aerosol loading, due to urbanism and more frequent dust storms, is reported to have occurred in the UAE and confirmed by increasing trends of poor visibility (Aldababseh and Temimi, 2017). The average aerosol optical depth in the UAE has been found to exceed 0.4, reaching maximum values of 1.0 during the summer season (Eck et al., 2008; Gherboudj and Ghedira, 2014). The region’s aerosol loading could also be contaminating CLARA-A2 algorithms, resulting in misclassification of aerosols and clouds and causing higher reported TCC. Several studies of different products have also found that over arid areas with high surface albedo, the performance of cloud detection algorithms was compromised (Brennan et al., 2005; Jin et al., 2009; Zhuge et al., 2017). For the UAE, the high spectral reflectance of the region’s arid land surfaces has been reported to cause difficulty in remote sensing retrievals (Eck et al., 2008) as it saturates the satellite signal and makes the retrieval of clouds, especially thin ones, more challenging. CLARA-A2 has been found to report false clouds in areas of challenging surface emissivities, such as semi-arid regions like the Arabian Peninsula (Karlsson et al., 2017b).

Due to the known issues that might impact the reliability of the CLARA-A2 dataset for climatological investigations (e.g., varying numbers of satellites, sensor changes and orbital drifts), an assessment of its homogeneity is conducted over the study period. The Pettitt test (conducted at the 10% significance level) detects two significant change points: the first in 1991 (Dubai, Sharjah and Ras Al Khaimah), and the second in 1998 (Al Ain, Abu Dhabi, Dubai and Fujairah). The 1998 change is also detected by the CUSUM test.

Karlsson et al. (2017a) and Karlsson et al. (2017b) provide information and discussion on potential sources of artifacts in CLARA-A2. Only one NOAA satellite at a time was in orbit recording two measurements a day over the UAE (NOAA-7, NOAA-9 and NOAA-11 respectively) at the beginning of the study period. After 1991–1992, the number of satellites was increased to two at a time (NOAA-11 and NOAA-12, followed by NOAA-12 and NOAA-14, etc.), which is the probable cause for the break in the time series occurring in 1991. Further increases in the number of satellites occurred after 2002, though no change points were detected. The AVHRR/3 sensor was introduced in 1998, which could have induced the change point occurring in that year. Interestingly, the Pettitt test reveals a statistically significant change point in the filtered ground observations occurring in 1998 (Al Ain, Sharjah, Ras Al Khaimah and Fujairah), which is confirmed again by the CUSUM test for all six stations. Therefore, the change occurring in 1998 in CLARA-A2 could be caused by both artifact and natural phenomena, and requires further investigation.

The CLARA-A2 time series is divided into subsamples in order to evaluate the homogeneity of means and variances before and after the change points, through applying the Student’s t test and Levene’s test (at the 10% significance level). For the subsamples before and after 1991, the means are
homogenous for all stations except for Dubai. However, the variances of Al Ain, Abu Dhabi and Sharjah fail the homogeneity test for the same subsamples. The testing of subsamples before and after 1998 result in Dubai, Ras Al Khaimah and Fujairah failing the homogeneity of means test, while all stations except Abu Dhabi fail the homogeneity of variance test. The inhomogeneous characteristics displayed in the results of the statistical tests lead to the recommendation of exercising caution when using CLARA-A2 to evaluate trends of cloudiness in the region and suggest using unfiltered ground observations to study TCC climatology over the UAE.

4 UAE TCC CLIMATOLOGY FROM GROUND OBSERVATIONS

Monthly averages of TCC derived from the unfiltered ground observations are displayed in Figure 4 for the six stations. Table 1 and Figure 4 indicate that the Fujairah station, on the eastern side of the UAE, has the highest overall mean TCC, followed by Al Ain, while Sharjah and Abu Dhabi, on its western side, have the lowest, respectively. The urbanization of Fujairah and Al Ain has progressed at a slower rate than other parts of the UAE, specifically when compared to Dubai, Abu Dhabi and Sharjah (Wiedmann, 2012). Lazzarini et al. (2013) and Lazzarini et al. (2015) found that the central part of Abu Dhabi city exhibited inverted UHI behavior as the city’s land surface temperatures were lower than suburban sites. Therefore, UAE cities can be expected to have different effects on convection and TCC formation to what was reported in the U.S. city of Atlanta (Bornstein and Lin, 2000), and Russian cities (Romanov, 1999), which lie in subtropical and subarctic climate zones, respectively—namely, lower TCC than their less urbanized counterparts. Increased levels of anthropogenic aerosols over the urban cities have an influence on the formulation and lifetime of TCC, though further understanding is required as effects depend on the aerosol characteristics, the region and other

TABLE 2 True slopes of unfiltered ground observations for subsamples before and after 1998 change point using Theil-Sen’s estimator

| Station      | Annual | Fall | Winter | Spring | Summer |
|--------------|--------|------|--------|--------|--------|
|              | Before CP | After CP | Before CP | After CP | Before CP | After CP | Before CP | After CP | Before CP | After CP |
| Al Ain       | 0.04    | −0.11 | −0.10  | −0.11  | −0.06   | 0.41    | −0.37   | −0.40   | −1.76    | −0.11   |
| Abu Dhabi    | 0.29    | 0.31  | 0.02   | 0.31   | 0.53    | 0.77    | 0.24    | −0.02   | 0.23     | 0.42    |
| Dubai        | 0.28    | 0.08  | −0.04  | 0.14   | 0.83    | 0.62    | 0.15    | 0.12    | 0.15     | −0.15   |
| Fujairah     | −0.14   | −0.02 | 0.17   | −0.34  | −0.39   | 0.74    | −0.01   | −0.11   | −0.16    | −0.21   |
| Ras Al Khaimah | 0.17   | 0.24  | −0.10  | 0.04   | 0.61    | 0.83    | 0.15    | 0.24    | 0.13     | 0.09    |
| Sharjah      | 0.17    | 0.24  | 0.06   | 0.05   | 0.82    | 0.48    | 0.29    | −0.06   | 0.28     | −0.23   |
atmospheric effects (Stevens and Feingold, 2009; Li et al., 2011). The land-sea temperature difference, along with the presence of Al Hajar mountain chain along the eastern coast of the UAE, significantly influences TCC in Fujairah, leading to orographic cloud formations (Banta, 1990; Al Mandoos, 2005). Fujairah's vegetation can also enhance latent and sensible heat transfer, which increases convection and ultimately precipitation and cloudiness (Green et al., 2017). Fujairah also lies on the coast of the Gulf of Oman, making it more susceptible to the effects of the Indian Monsoon through proximity to the Arabian Sea (Bento, 2011).

The modified Mann Kendall test is conducted at the 10% significance level on the annual, monthly and seasonal means. Abu Dhabi and Ras Al Khaimah do not exhibit any statistically significant trends. The annual results show that in the less urbanized areas of Al Ain and Fujairah, a decreasing trend in TCC is present (though only statistically significant in Fujairah). For Al Ain, the months of July and August specifically exhibit significant decreasing trends, while for Fujairah a significant decrease is found in April. Annually, the more urbanized cities do not exhibit significant TCC trends. In the fall, specifically in November, Sharjah displays a significant increasing trend. Dubai exhibits a significant decrease in the spring, specifically in the months of April and May.

The Pettitt test reveals a statistically significant change point (at the 10% level) occurring in 1998 for Al Ain, Sharjah, Ras Al Khaimah and Fujairah (similar to filtered observations’ results). The CUSUM test also detects a change point occurring during 1998 for all six stations. True slopes in TCC are then examined using the Theil-Sen’s estimator, with the annual and seasonal slopes before and after the 1998 change point shown in Table 2. For most stations, increasing trends are confirmed through the positive slopes. Notable increasing trends are also found for the winter season.

The time series of the ONI is shown in Figure 5, with the phase change occurring in 1998 highlighted. The “warm phase” occurring in 1997–1998 and the subsequent cooling correspond to the change in TCC that occurs in 1998, confirming the potential link of TCC trends in the region to ENSO. The detrended time series of ONI running means is correlated with the detrended monthly TCC means, such that the third month used for the sea surface temperatures mean corresponds to the month of the TCC value. The Spearman rank correlation coefficients are presented in Table 3. The results show that during the fall season (October predominantly), statistically significant correlations that suggest a teleconnection for TCC with ENSO exists. The winter–spring season (February to May) also exhibits a link. Ouarda et al. (2014) find similar results for the precipitation regime in the UAE, with a change point in 1999 linked to equatorial Pacific sea surface temperatures. The findings of several other studies support this teleconnection (Park and Leovy, 2004; Athar, 2015), which is caused by shifts of the upper level STJ stream towards the Equator during the positive El Niño phase causing shifts in Rossby waves propagation, ultimately affecting moisture in the region (Hoskins and Karoly, 1981; Sardeshmukh and Hoskins, 1988; Shaman and Tziperman, 2011; Niranjan Kumar and Ouarda, 2014).
CONCLUSIONS

TCC is analyzed over six stations in the UAE between 1984 and 2009, using ground observations and CLARA-A2 measurements. Differences in reports between ground observations and CLARA-A2 reports vary depending on the ranges of TCC and day/night conditions. Potential causes for these differences are human errors and region-specific challenges for remote sensing retrievals. The investigation of CLARA-A2 homogeneity over the study period reveals change points occurring in 1991 and 1998, with further studies of mean and variance homogeneity for subsamples between change points confirming artifact-induced inhomogeneities in the dataset. One difference in the two change points is that the one occurring in 1998 is theorized to be a combination of artificial and natural components, as the filtered ground observations exhibit a change occurring at the same time.

The study of UAE TCC climatology using unfiltered ground observations explores the spatial differences between stations, attributed primarily to topography and urbanism. Most of the stations exhibit significant decreasing trends. The 1998 change point occurring in all stations, around the same period as an ENSO phase change, prompts the study of the potential teleconnection with ENSO, with results showing a strong link in the fall–winter seasons.

Different observation and measurement techniques result in the discrepancies found between ground and CLARA-A2 reported TCC records, and provide justification for further validation studies to be conducted.

ACKNOWLEDGEMENTS

The authors thank the UAE National Center of Meteorology for the airport observation records, which were provided under an agreement with clauses for nondisclosure of data. Access to this data is restricted and readers should request it through contacting research@ncms.ae. The CLARA-A2 data was obtained from the European Organisation for the Exploitation of Meteorological Satellites (EUMET-SAT) CMSAF website www.cmsaf.eu. The ONI values are obtained from the NOAA-CPC website http://origin.cpc.ncep.noaa.gov.

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How to cite this article: Yousef LA, Temimi M, Wehbe Y, Al Mandous A. Total cloud cover climatology over the United Arab Emirates. *Atmos Sci Lett*. 2019;20:e883. [https://doi.org/10.1002/asl.883](https://doi.org/10.1002/asl.883)