Anatomy of the Annular Solar Eclipse of 26 December 2019 and Its Impact on Land–Atmosphere Interactions Over an Arid Region

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Abstract—The impact of 26 December 2019 annular solar eclipse (ASE) on meteorological conditions over the southeastern Arabian Peninsula is investigated. Observations sourced from the spinning enhanced visible and infrared imager (SEVIRI) and vertical temperature profiles measured by a microwave radiometer were used. The ASE, which began at 03:36:37.9 Universal Time Coordinated (UTC), that is, 31 m 29.9 s after sunrise, left a significant imprint on the land surface temperature (LST). In particular, in some regions, the LST dropped by more than 4 °C, in comparison to the previous day. In situ soil properties, in particular soil texture, were also found to have modulated the effects of the ASE, with loamy soils experiencing higher heating/cooling rates than sandy soils. Finally, the analysis of atmospheric profiles indicated that the eclipse influenced the flow throughout the atmospheric boundary layer, with a stable layer that was 45-min longer and 90-m deeper compared with the preceding day.

Index Terms—Annular solar eclipse (ASE), arid region, microwave radiometer (MWR), spinning enhanced visible and infrared imager (SEVIRI) land surface temperature (LST).

I. INTRODUCTION

The incoming short-wave radiation from the Sun is one of the main governing forces of all the meteorological processes occurring in the atmosphere [1]. The eclipse of the Sun, which occurs when the Moon orbits between the Sun and our planet, may be considered as a short night in the midst of an ordinary day. Such an event can be regarded as an ideal “laboratory experiment,” distinct from what is typically observed during sunrise, sunset, and varying cloudiness [2]. Annular solar eclipses (ASEs) and total solar eclipses (TSEs) have attracted the attention of scientists over the years (e.g., [3]–[5]), with the majority of studies focusing on its atmospheric response (e.g., [6] and references therein).

It has long been known that the drops in the land surface temperature (LST) and air temperature are the most significant effects of a solar eclipse (e.g., [7], [8]). As detailed in Segal et al. [9], there are typically two ways to estimate the magnitude of the surface/air temperature drop following an eclipse: 1) compare its value with an early peak or 2) take the difference with respect to that estimated in a “noneclipse” day at the same time of the day. As noted by Good [10], the latter is generally 1–2 °C higher than the former and is the one typically reported in the literature and considered here.

The amplitude of the LST decrease depends on several factors such as the time of the day, the duration of the eclipse, local topography, the location of the site in particular with respect to water bodies, among others (e.g., [10]–[12]). For example, during the ASE in southern India in January 2010, decreases in temperature ranging from 5.4 °C at the surface to 2.5 °C at 15 m above the ground were observed [12], accompanied by relative humidity increases from 15% to 7%, respectively. The soil temperature dropped by more than 1 °C in the top 20 cm, below which no significant effect was observed. During a TSE in March 2015 over Europe [10], a median decrease in the LST of approximately 3.1 °C was reported. The authors noted a smaller LST drop over vegetated surfaces compared with urban and cropland areas, as well as at higher elevation sites compared with coastal regions. Founda et al. [8], who investigated the 29 March 2006 TSE across Greece, reported the opposite: a more significant LST drop at higher altitudes and with increased vegetation coverage. A possible explanation is the different soil texture and land use/land cover (LULC) and associated soil properties. As highlighted by Good [10], if a surface has a smaller thermal roughness length (e.g., bare soil when compared with a vegetated surface), the near-ground temperature gradient will be steeper, potentially leading to a reduced drop in LST. This highlights the role of the surface properties on the surface and atmospheric response to an eclipse. Both studies also noted that the LST changes are larger further away from the coast. At higher latitudes, Kameda et al. [13] noted a decrease in the 1.5-m temperature of about 3 °C during the 23 November 2003 TSE at Dome Fuji, Antarctica, whereas for the 20 March 2015 TSE in Svalbard, a drop smaller than the 0.5 °C uncertainty of the sensor was recorded [14]. It is important to note that the eclipse signal can still be detected even when the atmospheric conditions are not at all favorable (i.e., cloudy skies) [15].

In addition to the drops in the soil and near-surface air temperatures, ASEs/TSEs impact several meteorological processes such as the surface energy balance, mesoscale circulations such as sea-breezes, and turbulence in the boundary layer (e.g., [11], [12], [16], [17]). Ratnam et al. [12] found that as the ASE progressed, the lower level winds (below a height of about 200 m) decoupled from the atmospheric flow aloft and weakened, strengthening again after the end of the event. In a study of the same eclipse, Subrahmanyan et al. [18] reported that about 85% decrease in the incoming solar radiation led to lower turbulent kinetic energy and surface-layer turbulent fluxes, which accompanied a weaker and shallower sea/land-breeze circulation cell. Water evaporation from the surface...
was also reduced during an eclipse [19], and so was the ultraviolet (UV) radiation from the Sun, which exhibits a similar trend to that seen in the solar radiation [20]. While the effects of ASEs/TSEs have been studied extensively in several places, little attention has been given to their impacts in arid/hyperarid regions such as the United Arab Emirates (UAE). The UAE, a country located in the eastern part of the Arabian Peninsula (Fig. 1), has a relatively flat topography except on the eastern side where the Al Hajar Mountains rise to more than 3000 m above the mean sea level. The annual precipitation rates vary from under 40 mm in the southern desert to more than about 160 mm in the Al Hajar Mountains [21], [22], with a large interannual variability of cloudiness. In addition to dust and sand storms [23], fog events are frequent in the country in particular in the cold season (e.g., [24]–[26]). In this letter, the focus is on the 26 December 2019 ASE which affected the southeastern Arabian Peninsula, occurring just after the sunrise. The two main goals of the study are as follows: 1) to investigate the impact of the ASE on the surface temperature and the atmospheric boundary layer (ABL) structure in a hyperarid region and 2) to explore how the response to the ASE varies as a function of the surface properties with interest in soil parameters. This letter is structured as follows. The data sets and the methods are described in Section II. An overview of the ASE is given in Section III. The impact on the LST that was observed from space and on temperature vertical profiles as measured by a microwave radiometer (MWR) is discussed in Section IV. 

II. DESCRIPTION OF DATA AND PERIOD OF ANALYSIS

Two observational data sets are used in this work. 1) LST derived from the spinning enhanced visible and infrared imager (SEVIRI, [27]), an instrument on board Meteosat’s Second Generation Spacecraft (MSG), and 2) vertical temperature profiles from an MWR in Abu Dhabi [28]. ERA-5 reanalysis data [29], at 0.25° × 0.25° spatial resolution (≈27 km), are also used to inspect the large-scale atmospheric conditions.

The near real-time estimates of LST are made available by the land surface analysis satellite application facility (LSA SAF) at 15-min temporal and at the roughly 3-km native spatial resolution of the SEVIRI sensor (data available online at http://landsaf/meteo.pt/). The LSA SAF LSTs are estimated using the “split window” channels located at 10.8 and 12 μm using the generalized split window scheme given by Zhengming and Dozier [30]. The uncertainty in the derived LSTs ranges from 1 °C to 2 °C [31]. Furthermore, details about the LST estimates can be found in [10].

The RPG-HATPRO (G5 series) passive MWR, which operates in two frequency ranges [28], is located at 24°26’ 11” N and 54°36’ 43” E, about 4 km from Abu Dhabi’s International Airport. It measures temperature and humidity profiles every second at a minimum vertical resolution of 100 m in the lowest 10 km. A comparison of the vertical temperature profiles given by the MWR with those obtained from radiosondes launched at the nearby airport revealed that they are generally within 1 °C of each other, from the surface up to a height of 10 km. The humidity profiles, on the other hand, are very different, with biases that can exceed 6 g kg⁻¹ in particular in the lowest 2 km, possible because of a nonoptimal retrieval algorithm [28]. Therefore, only temperature profiles are considered in this study, and they are compared with those observed on the preceding noneclipse day, 25 December 2019, when the prevailing synoptic conditions were similar.

III. ASE OF 26 DECEMBER 2019

Fig. 1 shows the path of the 26 December 2019 ASE, downloaded from the National Aeronautic and Space Administration’s (NASA’s) website.¹ As seen in Table S1 (see the Supplementary Material), the ASE began at 03:35 Universal Time Coordinated (UTC), nearly 30–50 min after the local sunrise, and lasted roughly 3 min. The end of the partial solar eclipse occurred at 04:55 UTC.

Fig. 1 also shows the soil texture and the topography of the target region. The soil texture is generated from the ~9-km United Nations Food and Agriculture Organization global soil data [32]. Over the UAE, a higher resolution of soil texture data, provided by the UAE’s National Center of Meteorology, is plotted [33]. The topography over the UAE is given by a ~30-m data set generated by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT), whereas elsewhere it is obtained from a roughly 1-km data set provided by the US Geological Survey (USGS). The dominant soil textures along the ASE path are sandy, sandy loam, and clay mainly in the western part of the UAE. Fig. 1 also gives the location of the two stations along the ASE path and that of the MWR. The dominant soil texture at the location of station #1 and of the MWR is sand, while at the location of station #2 is sandy loam. Desert areas, when compared with the vegetated regions, are prone to higher amplitude temperature diurnal cycle, given the shorter time-scale response to the solar radiation [33], potentially exacerbating the ASE signal. As seen in Fig. 1(b), along the ASE path the elevation is generally below 500 m, meaning that the eclipse occurred mostly over low-lying regions.

IV. IMPACT OF ASE ON LST

Fig. 2 gives the 10-m horizontal winds, together with the surface skin temperature, total cloud cover, and precipitable water (i.e., total amount of water vapor in the atmosphere) on 26 December 2019 at 02 UTC, just before the local sunrise, from the ERA-5 reanalysis data. It is important to note that ground observations available for assimilation are scarce

¹https://eclipse.gsfc.nasa.gov/SEpath/SEpath2001/SE2019Dec26Apath.html
LST drop was reported in a tropical rural site in southern India in the 15 January 2010 ASE event [12], where an LST decrease of 5.4°C was observed for a mid-morning eclipse. In addition, in northern Zimbabwe, the 21 June 2001 TSE [6], which occurred in the local afternoon, led to a temperature drop of about 5°C. More recently, in the mid-morning partial eclipse in western Russia on 4 January 2011, and in the mid-to-late-afternoon TSEs over southwestern Russia and Siberia on 29 March 2016 and 1 August 2008 [35], respectively, the maximum surface temperature decrease was about 3.9°C. According to the above-mentioned studies, in arid regions, like the southeastern Arabian Peninsula, the response of the surface fields to the changes in the solar forcing is more pronounced.

Previous studies (e.g., [10], [12]) noted that the minimum in LST generally occurs around or shortly after the eclipse midpoint, reportedly 1.5–10 min. However, in the December 2019 case, a longer time lag of 22 min was noticed. This is not unprecedented as Kameda et al. [13], who analyzed this time lag for 17 eclipses, found a wide range of values, from 6 to 30 min, with the longest lag recorded for a TSE at Dome Fuji in Antarctica in 2003. The authors concluded that the time lag between the peak of the eclipse and the minimum in LST is a function of several variables, such as the surface conditions, horizontal wind speed, vertical convection, and the global solar radiation after the eclipse terminates. In fact, [13, Fig. 11] shows a correlation between the time lag and the global short-wave radiation at the end of the eclipse: for the 1994 ASE in the USA, the time lag was just 7 min with an incoming solar radiation of ~950 W m⁻²; for the 2003 eclipse in Antarctica, on the other hand, these figures were 269 W m⁻² and 30 min, respectively. In the present study, at location #2, the incoming short-wave radiation flux at 05 UTC, that is, at the end of the event, was 435.4 W m⁻², as estimated from the SEVIRI data, consistent with the lag of ~22 min. A comparison with the preceding noneclipse day, however, revealed comparable values of the downward short-wave radiation flux: for example, at 03:30 UTC the fluxes on 25 and 26 December 2019 were 106.7 and 105.3 W m⁻², respectively, whereas at 05 UTC they were 436.3 and 435.4 W m⁻², respectively.

Fig. 4 presents the evolution of the LST difference between the eclipse (26 December 2019) and the preceding noneclipse (25 December 2019) day, from 03:00 to 04:45 UTC. As seen, there is a significant reduction in the LST due to the ASE, with a magnitude exceeding 4°C in some regions in particular along its path, which is in line with previous studies [6], [10], [12]. Fig. 4 also highlights that the impact of the ASE is not restricted to the total eclipse region: for example, the warm anomaly over central and southern parts of Oman, well south of where the eclipse occurred, decreased during the ASE, slowly increasing thereafter. Furthermore, a similar comparison was done between LSTs on 26 December and 27 December, which revealed a similar pattern of LST differences, with the exception of Iranian coast which was covered with clouds. This strengthens the likelihood of the aforementioned decrease in LST being directly associated with the ASE, although the influence of other meteorological factors cannot be entirely eliminated. It is worth noting that knowledge of nonlocal impacts of eclipses on the surface meteorological fields is not new and has been reported, for example, in [7] and [16].

A comparison of Fig. 4 with Fig. 1(a) reveals that the soil texture has some influence on the LST’s response to the eclipse. For example, loamy sand regions cool down
more than the surrounding areas, consistent with the fact that these soils have a higher porosity than sandy soils [33]. A soil with higher porosity has a lower thermal inertia, exhibiting a faster response to the solar forcing. This is further confirmed when inspecting the cooling/heating rates (see Fig. S2 in the Supplementary Material). The link between the soil type and the correspondent temperature change is well-established in the literature. In fact, in [36], the lithological soil type in the arid regions of the Middle East and northern Africa was inferred from the diurnal cycle amplitude of the satellite-derived brightness temperature. Soils with reduced diurnal temperature variability are more likely to be composed of loose siliceous rocks, whereas those composed primarily of argillaceous, carbonate, and evaporite rocks exhibit large-amplitude diurnal cycles. A comparison of [36, 4] with Fig. S2 (see the Supplementary Material) indicates that the soil lithology impacted the LST response to the eclipse: for example, the cooling/heating rates are generally larger over Oman, where the soil is primarily composed of carbonates, argillaceous, and evaporite rocks.

To investigate whether the ASE’s effects are limited to the surface fields, in Fig. 5 vertical temperature profiles, as measured by an MWR located in Abu Dhabi [28] at the location highlighted by a circle in Fig. 1, are given. Even though this site is just outside the penumbra, as seen in Fig. 4, it experienced a slower rate of warming after sunrise. It is important to stress that a full understanding of the impact of the ASE on the boundary layer structure would require an analysis of the moisture profiles as well. However, given the large biases in this field reported in [28], such an analysis cannot be conducted.

Fig. 5(a) shows the observed air temperature during the eclipse (red line) and the preceding noneclipse (green line) day, as measured by a temperature sensor collocated with the MWR. The difference between the two temperatures is plotted in Fig. 5(b). Nearly, 20 min after the maximum solar eclipse, the air temperature reached the minimum value of 13.4 °C, before steadily recovering with respect to that measured on the previous day, in particular after the end of the eclipse. This variability is broadly consistent with that of the LST at location #2 [Fig. 3(c) and (d)]. The cooler temperatures on 26 December compared with those on the preceding day from about 01–03 UTC are likely due to cold air advection from the inland desert, as according to the ERA-5 data, the wind direction was easterly to southeasterly at that time (see Fig. 2). As a result of cold temperatures, the nighttime boundary layer is more stable, with a sharper inversion aloft, seen in Fig. 5(c). After the sunrise at ~03 UTC, the surface gradually warmed up to 14.7 °C, but then it cooled down to 13.4 °C just before 04 UTC, due to the decrease in the incoming short-wave solar radiation [see Fig. 5(a)]. This cooling occurs not just at the surface but also in the lower atmosphere, as highlighted in Fig. 5(d), which shows the average profiles between 03:30 and 04:55 UTC, that is, from eclipse peak to end timings. In Fig. 5(e), between 05:00 and 06:30 UTC, the stable layer persisted on the eclipse day, while on 25 December 2019 it was being eroded, with a nearly isothermal profile in the lowest 200 m. Around local noon and in the early afternoon hours [Fig. 5(f)] and even though the stable layer is completely eroded, the vertical temperature profiles on the eclipse day are slightly cooler below 340 m compared with those on the preceding day. This indicates that the effects of the ASE persisted well after it ended, which is in line with the published work [12]. A quantitative evaluation yielded that the near-surface stable layer reached a maximum depth of 220 m on 25 December and 310 m on 26 December, with it lasting longer in the latter by approximately 45 min. During the TSE on 29 March 2006 and the partial eclipse on 4 January 2011 in western Russia, Kadygrov et al. [35] noted that the decrease in surface temperature was roughly 2 °C larger than that at 600 m height. Here, however, they are of a comparable magnitude, 1 °C (not shown). A possible explanation is the increased vertical mixing in this arid region, compared with the colder environment in Russia, particularly in spring and winter.

V. Summary

In this letter, the effects of the 26 December 2019 ASE on the LST and ABL over the southeastern Arabian Peninsula are analyzed using a combination of remote sensing observations. Namely, the 15-min LST derived from the SEVIRI instrument on board MSG and the 1-min vertical temperature profiles from the MWR are considered, together with hourly ERA-5 reanalysis data. When compared with the preceding and following noneclipse days, the LSTs were up to 6 °C lower in particular along the ASE region during the event. This magnitude is on the higher side of that reported by other authors (e.g., [10]), which is consistent with the fact that arid/hyperarid regions exhibit a stronger response to the changes in the Sun’s short-wave radiation flux, when compared with the temperate/vegetated areas.

An analysis of the spatial LST change revealed that the cooling of the surface in response to the eclipse is not...
restricted to the eclipse region. It extends well beyond the penumbra. In addition, and in line with a previous work [18], the ASE signal also extends to the low levels of the atmosphere, with a deeper stable layer during the event by about 90 m, which also lasted roughly 45 min longer after sunrise. The lack of humidity profiles precludes a more in-depth analysis of the impact of the ASE on the boundary layer height. What is more, the soil texture likely modulated the LST response to the ASE: for example, loamy sand regions tend to be cooler than sandy regions due to their higher porosity and hence lower thermal inertia. The soil lithological type also influenced the LST response, with soils dominated by carbonates, argillaceous, and evaporite rocks experiencing the largest cooling/heating rates, in line with the findings of [36]. An extension of this work would be to simulate the eclipse with a numerical model to gain further insight into its impact on the atmospheric dynamics.

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REFERENCES

[1] R. B. Stull, An Introduction to Boundary Layer Meteorology. Dordrecht, The Netherlands: Springer, 1988.
[2] T. Foken, B. Wichura, O. Klemm, J. Gerchau, M. Winterhalter, and T. Weidinger, “Micrometeorological measurements during the total solar eclipse of August 11, 1999,” Meteorologische Zeitschrift, vol. 10, no. 3, pp. 171–178, May 2001.
[3] N. Kolev et al., “Aerosol Lidar and in situ ozone observations of the planetary boundary layer over Bulgaria during the solar eclipse of 11 August 1999,” Int. J. Remote Sens., vol. 26, no. 16, pp. 3567–3584, Aug. 2005.
[4] E. J. Seykora, A. Bhatnagar, R. M. Jain, and J. L. Streeve, “Evidence of atmospheric gravity waves produced during the 11 June 1983 total solar eclipse,” Nature, vol. 313, no. 5998, pp. 124–125, Jan. 1985.
[5] B. M. Varney, “Notes on changes in some of the weather elements during the solar eclipse of January 24, 1925,” Monthly Weather Rev., vol. 53, no. 2, pp. 21–22, Jan. 1925.
[6] K. L. Aplin, C. J. Scott, and S. L. Gray, “Atmospheric changes from solar eclipses,” Phil. Trans. Roy. Soc. A, Math., Phys. Eng. Sci., vol. 374, no. 2077, pp. 106–127, May 2017.
[7] M. Weston, N. Chauoch, V. Valappil, M. Temimi, M. Ek, and W. Zheng, “Assessment of the sensitivity to the thermal roughness length in Noah and Noah-MP land surface model using WRF in an arid region,” Pure Appl. Geophys., vol. 176, no. 5, pp. 2121–2137, May 2019.
[8] J. Schmetz et al., “An introduction to Meteosat second generation (MSG),” Bull. Amer. Meteorol. Soc., vol. 83, no. 7, pp. 977–992, 2002.
[9] M. Temimi et al., “On the analysis of ground-based microwave radiometer data during fog conditions,” Atmos. Res., vol. 231, Jan. 2020, Art. no. 104652.
[10] H. H. Clayton, “Clayton’s eclipse cyclone and the diurnal cyclones,” Science, vol. 13, no. 332, pp. 747–750, May 1901.
[11] D. Founda et al., “The effect of the total solar eclipse of 29 March 2006 on meteorological variables in Greece,” Atmos. Chem. Phys., vol. 7, pp. 5543–5553, Nov. 2007.
[12] M. Segal, R. W. Turner, J. Prusa, R. J. Bitzer, and S. V. Finley, “Solar eclipse effect on air temperature,” Ball. Amer. Meteorol. Soc., vol. 77, no. 1, pp. 89–99, Jan. 1996.
[13] E. Good, “Satellite observations of surface temperature during the march 2015 total solar eclipse,” Phil. Trans. Roy. Soc. A, Math., Phys. Eng. Sci., vol. 374, no. 2077, Sep. 2016, Art. no. 20150217.
[14] K. G. Rao et al., “Near surface atmospheric response to the total solar eclipse at Dibrugarh on 22 July 2008,” J. Atmos. Solar-Terr. Phys., vol. 95–96, pp. 87–95, Apr. 2013.
[15] M. V. Ratnam, M. S. Kumar, G. Basha, V. K. Anandan, and A. Jayaraman, “Effect of the annular solar eclipse of 15 January 2010 on the lower atmospheric boundary layer over a tropical rural station,” J. Atmos. Solar-Terr. Phys., vol. 72, no. 18, pp. 1391–1400, Dec. 2010.
[16] T. Kameda, K. Fujita, G. Sugita, N. Hirasawa, and S. Takahashi, “Total solar eclipse over Antarctica on 23 November 2003 and its effects on the atmosphere and snow near the ice sheet surface at Dome Fuji,” J. Geophys. Res., vol. 114, no. D8, pp. 1–15, 2009.
[17] J. M. Pasachoff, M. A. Pehalaolo-Murillo, A. L. Carter, and M. T. Roman, “Terrestrial atmospheric responses on Svalbard to the 20 March 2015 Arctic total solar eclipse under extreme conditions,” Phil. Trans. Roy. Soc. A, Math., Phys. Eng. Sci., vol. 374, no. 2077, Sep. 2016, Art. no. 20160188.
[18] M. A. Pehalaolo-Murillo and J. M. Pasachoff, “Cloudiness and solar radiation during the longer total solar eclipse of the 21st century at Tianhuangping (Zhejiang), China,” J. Geophys. Res., Atmos., vol. 123, no. 23, pp. 413–443, Dec. 2018.
[19] K. L. Aplin and R. G. Harrison, “Meteorological effects of the eclipse of 11 August 1999 in cloudy and clear conditions,” Proc. Roy. Soc. London. Ser. A, Math., Phys. Eng. Sci., vol. 459, no. 2030, pp. 353–371, Feb. 2003.