Impact of 21 June 2020 annular solar eclipse on Meteorological parameters, O3 and CO at a high mountain site in Taiwan

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Abstract
The annular solar eclipse observed on 21 June 2020 over Taiwan provided a rare opportunity to follow the responses of various meteorological parameters and trace gases to the solar eclipse. For the first time, the impact of the solar eclipse on solar radiation, air temperature (T), relative humidity (RH), atmospheric pressure (P), wind speed (WS), and trace gases (ozone and carbon monoxide) is delineated at the Lulin Atmospheric Background Station (LABS; 23.47°N, 120.87°E; 2,862 m MSL) in Taiwan. Over the Taiwan region, the solar eclipse began at 14:49 local time (LT; UTC+8), reached maximum obscuration at 16:13 LT, and finished at 17:24 LT. Compared to the control period (average of 13–20 June 2020), the weather parameters and trace gases show pronounced changes on the day of the eclipse (21 June 2020). A significant decrease in UV-B and solar irradiance at LABS was observed during the peak phase of the solar eclipse due to the occultation of the Sun by the Moon. On the eclipse day, the T decreased significantly (~4°C) after 17 minutes of maximum solar darkening. Due to the cloudiness and low temperatures on the day of the eclipse, 100% RH was apparent during the period of the eclipse at LABS. We also noticed a steady decline in WS just after the onset of the eclipse at LABS. Interestingly, a marked decline in ozone and carbon monoxide was seen during the eclipse day at LABS. Ozone was reduced by about 10 ppb (40%), with a delay of about 2 hours from the peak phase of the eclipse. Overall, our results show the impact of the solar eclipse on high altitude measurements for the first time, and further this work provides a useful new contribution to the literature examining solar eclipse-induced atmospheric changes.

Keywords: Solar eclipse, Lulin Atmospheric Background Station, Trace gases, Solar radiation
INTRODUCTION

The solar eclipse (i.e., total or partial, or annular) is a rare natural phenomenon when the Moon masks the solar disc for a shorter duration. During a solar eclipse, the insolation change is more rapid than in the evening and morning, making this astronomical event attractive from a meteorological and photochemical processes perspective. Hence, these events provide an excellent opportunity to investigate the spontaneous changes in the different meteorological, chemical and physical changes in the lower troposphere due to sudden changes in solar radiation. Temperature, solar irradiance, relative humidity, and wind are among the most common meteorological parameters, and the surface/atmospheric ozone (O$_3$) is the most photochemical parameter explored by previous studies of solar eclipses (Anderson, 1999; Szalowski, 2002; Founda et al., 2007; Nymphas et al., 2009; Naja and Lal, 1997; Abram et al., 2000; Tzanis et al., 2008; Nishanth et al., 2011; Girach et al., 2012; Ratnam et al., 2010 and references therein). The surface temperature received broad attention historically, and a noticeable drop in the temperature was well reported in the literature (Hanna, 2000; Aplin et al., 2016; Ratnam et al., 2010; Eugster et al., 2017; Hanna, 2018). However, the time response and magnitude of the reduction were quite varied. Some studies have reported an immediate drop in temperature (Szalowski, 2002), and some have reported a delayed response to the eclipse (Srivastava et al., 1982). A detailed review of temperature drops reported in various studies during a solar eclipse can be found in Eugster et al. (2017). Recent studies reveal a decrease in wind speed during eclipse events. This is attributed to the combined effect of a reduction in the thermal gradient and the stabilization of the surface layer due to the temperature drop (Amiridis et al., 2007; Subramanyam and Anurose, 2011; Namboodiri et al., 2011; Subrahmanyam et al., 2013).
Since solar eclipse produces significant sharp modulation in the solar intensity, it provides an excellent opportunity to examine the atmospheric O3 changes. The production and destruction of O3 were firmly controlled by solar radiation involving several trace gases, meteorology, and dynamics. Previously, several researchers have described the effect of the solar eclipse on surface/atmospheric O3 changes (Abram et al., 2000; Zanis et al., 2001, 2007; Tzanis et al., 2008). For example, Zanis et al. (2001) reported a decrease of about 10 to 15 ppb in surface O3 at an urban site in Thessaloniki, Greece, during a 90% solar obscuration on 11 August 1999. Tzanis et al. (2008) studied the behavior of surface O3 concentration in Athens, Greece, during the solar eclipse of 29 March 2006. They observed that the maximum reduction in surface O3 concentration occurred one hour after the maximum obscuration in Athens. Recently, Girach et al. (2012) reported a lowering of surface O3 by 12 and 13 ppb (35% and 52%) over two nearby tropical locations, with a time lag of 40 min and 25 min from the maximum phase of an annular solar eclipse, respectively. Although several researchers have investigated the relationship between surface/atmospheric O3 changes and solar eclipse events, a clear understanding of the O3 variations during the events is still sparse. One can notice that most of the previous studies were based on ground stations or urban locations and from either the Indian region or USA or Greece or the UK. However, studies on the solar eclipse-induced effects on surface/tropospheric O3 and different meteorological parameters are not yet reported, particularly over the western Pacific.

On 21 June 2020, an annular solar eclipse was visible along with Taiwan from Africa, India through China. The magnitude of the present annular solar eclipse was about 0.994. The path of the annular solar eclipse on 21 June 2020 is shown in Fig. 1. The eclipse started in the Democratic Republic of the Congo in Africa at 04:47 UTC, passed through Saudi Arabia, Pakistan, and China, and ended over the Pacific Ocean at 08:32 UTC, with the maximum eclipse obscuration occurring.
at 30.5°N, 79.7°E at 06:40 UTC. The partial eclipse covered a much more comprehensive range
and was visible for a width of thousands of kilometers from the main path from 03:51 UTC to
09:28 UTC. Over Taiwan, the annular solar eclipse began at 14:49 LT (06:49 UTC), reached the
maximum obscuration at 16:13 LT (08:13 UTC), and ended at 17:24 LT (09:24 UTC). This annular
eclipse is the only event that crossed over Taiwan, and it provides us an excellent opportunity to
study and understand the different meteorological and photochemical processes during the solar
eclipse period over Taiwan. In the present study, we investigated the likely changes in O3 and other
meteorological parameters during this rare eclipse event over Taiwan, mainly focusing on how
these meteorological and photochemical parameters can change at a high-altitude mountain site in
Taiwan.

2 MEASUREMENTS, DATA, AND METHODOLOGY

2.1 Study location

The present study was carried out at a high-altitude mountain station, namely Lulin Atmospheric
Background Station (LABS; 23.47°N, 120.87°E; 2862 m MSL) shown in Fig. 1 (marked star
symbol). LABS is located inside Jade Mountain National Park, part of the Central Mountain Range
(http://lulin.tw/en/) and is the first high-altitude background station in East Asia, and complements
the Global Atmospheric Watch (GAW) network. Over Taiwan, the southwest monsoon prevails
in summer, whereas the northeast monsoon prevails between late fall and spring. Owing to the
mountain–valley (M-V) circulation, LABS is frequently located in the free troposphere, and is
generally free from surface pollution in the boundary layer (Sheu et al., 2010; Ou-Yang et al., 2012,
2014). Additionally, since the westerlies prevail at a higher elevation in spring (Ou Yang et al.
2012, 2014; Ravindra Babu et al., 2022), LABS is affected by pollution outflows from Southeast Asia and the Asian continent.

Fig. 1. The path of the annular solar eclipse on 21 June 2020. The Lulin Atmospheric Background Station (LABS) is marked with a star symbol.

2.2 Measurements

High temporal resolution (every one minute) measurements of solar radiation, temperature, relative humidity, atmospheric pressure, wind speed, O3, and carbon monoxide (CO) at LABS were utilized in the present study. The O3-mixing ratio was measured at the LABS using a UV photometer (EC9810B, Ecotech, Australia). The O3 analyzer was calibrated using a traveling secondary standard calibrated to a standard UV O3 meter maintained by the Taiwan EPA. The CO mixing ratio was obtained by an NDIR (APMA-360, Horiba, Japan) at the LABS (Ou-Yang et al., 2022). Detailed instrumentation descriptions and analytical aspects for O3 and CO measurement can be found elsewhere (Ou-Yang et al., 2012, 2014, 2022).
Fig. 2. Himawari Satellite true-color images of 21 June 2020 at different timings. The approximate location of Taiwan is also marked manually with a box in the figure. Due to the eclipse, Taiwan was fully under darkness during the eclipse period.

3 RESULTS AND DISCUSSION

Each solar eclipse, depending upon its time of occurrence, duration, background synoptic conditions, season, and geographical location, has a unique effect on the Earth's atmosphere (Founda et al., 2007). Indeed, the 21 June 2020 annular solar eclipse provided an opportunity to investigate the different meteorological and trace gas changes over a high-altitude mountain site.
in Taiwan. This was the first annular solar eclipse to be observed in Taiwan, and the path of the eclipse was exactly overpassed through central Taiwan.

3.1 Changes observed in the Solar radiation

Fig. 3a and 3b depict the variation of Ultraviolet Radiation-B (UV-B) and the solar irradiance on the eclipse day (red color) and control period (blue color). One can note that for the control period, we have averaged the data between 13 June to 20 June, respectively. The error bars in the figure show a standard deviation in the respective parameters for the control period. The daily pattern of the UV–B and solar irradiance is similar during the eclipse and the control period, except for the eclipse period. Significant fluctuations in the UV-B and solar irradiance are noticed during the eclipse day, mainly from 10:00 LT onwards at LABS. These fluctuations may be due to cloud cover at LABS during the current eclipse event. The satellite figures clearly show the presence of pronounced clouds on the eclipse day over Taiwan (Fig. 2). Due to the presence of clouds, significant fluctuations were noticed in the solar irradiance during the eclipse day. However, around 14:49 LT, the eclipse arrived in this region.
Fig. 3. Variations in (a) solar irradiance and (b) ultraviolet radiation (UV-B) were observed at Lulin Atmospheric Background Station (LABS) during the annular solar eclipse on 21 June 2020. Vertical solid lines indicate the beginning, maxim, and end time of the eclipse.
The beginning (first contact: FC), maximum (maximum eclipse: ME), and the end of the solar eclipse (last contact: LC) are marked as FC, ME, and LC in the figure with vertical lines. Soon after the onset of the eclipse (14:49 LT), the solar irradiance data started to decline from its peak of about ~250 W m\(^{-2}\) and reduced to 0 Wm\(^{-2}\) at 16:10 LT, respectively. The time of minimum solar irradiance exactly coincided with the maximum totality of the eclipse in this region. After that, the solar irradiance steadily increased until the partial eclipse ended around 17:24 LT, and subsequently, solar radiation declined following the diurnal cycle. The changes observed in the solar radiation parameters have been in the range of earlier reported studies on similar annular solar eclipse events of 15 January 2010 (Ratnam et al., 2010; Girach et al., 2012).

3.2 Changes observed in the Meteorological parameters

Fig. 4 (a-d) illustrates the diurnal variations in basic meteorological parameters such as temperature, relative humidity, atmospheric pressure, and wind speed on the eclipse day of 21 June 2020 and the control period observed at LABS. All the meteorological parameters exhibit significant diurnal variability at LABS during the control period. For example, in Fig. 4a, the temperature increases after 6:00 LT and reaches its maximum ~11:00 LT. After that, the temperature gradually decreased at LABS. Like the control period, the temperature on eclipse day also shows an apparent diurnal variation. As cloud cover and rain also significantly impact temperature, colder temperatures are evident before the eclipse contact over Taiwan. However, the maximum lowering of temperature compared to the control period was noticed during the eclipse and shortly after the eclipse period. One of the most dramatic meteorological impacts of this solar eclipse is a change in surface temperature. At LABS, a maximum lowering of 4°C in the temperature compared to the control period has been observed around 16:27 LT after the maximum
eclipse obscuration (16:10 LT). However, the daily minimum temperature (~9°C) for the eclipse
day was recorded after the eclipse around 18:40 LT, respectively. After that, the temperature
gradually increased and reached similar to control period values during the nighttime. The
maximum drop in the temperature at LABS during eclipse day is well-matched with several
previous studies (Anderson, 1999; Tzanis et al., 2008; Girach et al., 2012). Anderson (1999)
reported that the minimum value of temperature was observed with a time lag of 5 and 20 min
with peak eclipse time. Similarly, Girach et al. (2012) reported a decrease in temperature by 1.2
°C over Thumba, India during the annular eclipse of 15 January 2010 with a time lag of 13 min
from the maximum phase of the eclipse. The time lag between maximum eclipse obscuration and
temperature minimum may be caused by the thermal inertia of the atmospheric surface layer (Aplin
and Harrison, 2003).

Compared to the control period, the atmosphere has also been colder, with higher relative
humidity in the night hours on the eclipse day (Fig. 4b). The eclipse event occurred in the monsoon
season, and it is typical to observe a colder day with ~100 % relative humidity in the afternoon
and evening hours. In the control period, the RH exhibited lower values ranging from 60 to 70%
during early morning and night. During afternoon times, particularly from 11:00 LT onwards, it
showed a gradual increasing pattern and exhibited higher values up to evening. This is mainly due
to the regular afternoon thunderstorm over LABS during the monsoon period. Like the control
period, RH followed the same pattern on eclipse day. However, due to cloud cover and afternoon
thunderstorm-associated rain on eclipse day, the RH exhibited 100% during the entire period.
Relative humidity quickly decreased to near 60% or lower following the eclipse. As solar radiation
returned, air temperature increased, and relative humidity declined to close to the pre-eclipse levels.
Pronounced changes observed in solar radiation and temperature also lead to changes in wind
speed during the eclipse. The observed wind speed during eclipse day and control period is illustrated in Fig. 4d. Wind speed showed enhanced values compared to the control period value until the onset of the eclipse. But immediately after the beginning of solar obscuration, it began to reduce, and the highest reduction in wind speed occurred at the maximum phase of the eclipse. At LABS, wind speed declined from its maximum of about 4 m s\(^{-1}\) to 1 m s\(^{-1}\) during the eclipse. It is suggested that the decline and subsequent absence of solar forcing during the progression of and during the total solar eclipse, respectively, resulted in the decrease in wind speed and the near-calm conditions. After completing the eclipse, the wind speed again started to increase.
Fig. 4. Variations in (a) temperature, (b) relative humidity, and (c) wind speed were observed at Lulin Atmospheric Background Station (LABS) during the annular solar eclipse on 21 June 2020. Vertical solid lines indicate the beginning, maxim, and end time of the eclipse.

3.3 Changes observed in the trace gases

Studies in the past during the solar eclipse have reported a range of O₃ variations (10-60%) depending on the observation site, eclipse intensity, and local meteorology (Fabian et al., 2001; Naja and Lal, 1997; Sharma et al., 2010; Tzanis, 2005; Zanis et al., 2007). In the present study, we also investigated the O₃ and CO changes during the eclipse event at LABS. Fig. 5a and 5b show the daily observed temporal pattern of O₃ and CO on eclipse day along with the control period at LABS. The control period observations of O₃ and CO show clear diurnal patterns at LABS and are pretty different from those reported at the surface stations, respectively. CO shows maximum levels in the late afternoon and minimum at night. O₃, however, shows a nearly opposite cycle to CO. The daily pattern of O₃ is characterized by a maximum around midnight and a minimum during noontime. The mountain-valley circulation controlled this diurnal variation in the O₃, as reported by previous studies from LABS (Ou-Yang et al., 2014). During the daytime, upslope flow brings boundary layer air to the summit, and this air is more humid and usually lows in O₃. Similarly, during nighttime, downslope flows bring free tropospheric air to the summit, and this air is dry and generally high in O₃.

The reduction in the O₃ concentration started precisely after the beginning of the eclipse at 14:49 LT and reached a minimum (~16.5 ppb) after the solar eclipse. It was observed that the reduction in O₃ is about 40%, with a time lag of ~2 hours from the maximum phase of the eclipse. A similar decrease in the CO at LABS was noticed. Further, we estimated the hourly mean values
of O₃ and CO during and after the eclipse on 21 June 2020, as shown in Table 1. It is evident that during regular days, the O₃ shows a continuous increasing pattern from 15:00 LT onwards and reaches a maximum at 22:00 LT. In the case of CO, the maximum value was noticed at 18:00 LT; after that continuous decreasing pattern was observed. As observed in Fig. 5, a constant decrease of O₃ and CO from 15:00 to 19:00 LT was noticed on eclipse day. It is clear that at 19:00 LT, the O₃ and CO exhibited minimum values on eclipse day compared to the control period. Studies conducted at various locations over the globe have revealed that solar eclipse causes changes of different magnitudes and temporal scales in O₃. For example, Naja and Lal (1997) observed a decrease of 18-21% at Ahmedabad during the solar eclipse of 24 October 1995, and Abram et al. (2000) reported a reduction of 8% of O₃ at Silwood Park, Ascot, during the solar eclipse of 11 August 1999. Tzanis et al. (2008) observed a higher rate of change in O₃ one hour after the maximum phase of the solar obscuration over four observation centers in Greece during the solar eclipse of 29 March 2006. Girach et al. (2012) reported a decrease in surface O₃ by 12 ppb (35 %) over Thumba, India during the annular eclipse of 15 January 2010 with a time lag of 40 min from the maximum phase of the eclipse. Jain et al. (2020) analyzed direct and indirect photochemical impacts on O₃ during the annular solar eclipse on 26 December 2019 over a tropical rural location in south India, and a 48 % reduction in O₃ concentration was reported 52 min of the time lag from the peak obscuration. Overall, the observed O₃ changes at LABS during the eclipse event agreed with the previous studies. However, we noticed a higher time lag for the maximum drop in the O₃ from the full phase of the eclipse compared to the other reported studies.
Fig. 5. Observed variations in (a) ozone and (b) carbon monoxide at Lulin Atmospheric Background Station (LABS) during the annular solar eclipse on 21 June 2020. Vertical solid lines indicate the beginning, maxim, and end time of the eclipse.
Table 1. Average values of O$_3$ and CO concentrations at 1-hour intervals during and after the period of eclipse (1500–2300 Local time 21 June 2020) as well as during the control period.

<table>
<thead>
<tr>
<th>Time</th>
<th>O$_3$ control period</th>
<th>O$_3$ eclipse day</th>
<th>CO control period</th>
<th>CO eclipse day</th>
</tr>
</thead>
<tbody>
<tr>
<td>15:00</td>
<td>23.4</td>
<td>23.2</td>
<td>82.7</td>
<td>72.7</td>
</tr>
<tr>
<td>16:00</td>
<td>25.5</td>
<td>22.8</td>
<td>84.7</td>
<td>67.5</td>
</tr>
<tr>
<td>17:00</td>
<td>25.9</td>
<td>22.1</td>
<td>86.5</td>
<td>68.3</td>
</tr>
<tr>
<td>18:00</td>
<td>26</td>
<td>19.8</td>
<td>86.6</td>
<td>65.8</td>
</tr>
<tr>
<td>19:00</td>
<td>26.9</td>
<td>17.4</td>
<td>85</td>
<td>61.6</td>
</tr>
<tr>
<td>20:00</td>
<td>29.4</td>
<td>20.1</td>
<td>83.2</td>
<td>62.5</td>
</tr>
<tr>
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<td>31.3</td>
<td>21.1</td>
<td>78.1</td>
<td>62.2</td>
</tr>
<tr>
<td>22:00</td>
<td>31.5</td>
<td>17.8</td>
<td>75.4</td>
<td>60.4</td>
</tr>
<tr>
<td>23:00</td>
<td>30.5</td>
<td>17.1</td>
<td>74.6</td>
<td>59.8</td>
</tr>
</tbody>
</table>

4 CONCLUSIONS

The solar eclipse observed on 21 June 2020 over Taiwan provided a rare excellent opportunity to follow responses of various meteorological parameters and trace gases to an eclipse event. For the first time, the impact of an annular solar eclipse on different meteorological parameters and trace gases at a high-altitude background station over Taiwan was investigated. The Lulin Atmospheric Background Station (LABS), located at Mt. Lulin in central Taiwan, was established to monitor the atmospheric compositions and radiation in the lower free troposphere of East Asia in 2006. This paper uses high temporal resolution measurements to investigate the impact of the 21 June 2020 eclipse event on different meteorological and trace gas species at LABS. The measurements on eclipse day were compared with the average of previous one-week data and
made conclusions in the study. In line with previous studies, the different meteorological
parameters and trace gases abruptly changed on eclipse day (21 June 2020) compared to the control
period (13-20 June 2020). The major findings obtained from the present study are summarized
below:

- A significant reduction in solar irradiance of approximately 250 W m\(^{-2}\) to 0 W m\(^{-2}\) was
  observed shortly after the start of the eclipse (14:49 LT).
- The temperature decreased ~4°C after 17 minutes of the maximum solar eclipse. The
  atmospheric pressure was also reduced by 2.1 hPa during the eclipse period.
- Due to the cloudiness and low temperatures on the day of the eclipse, 100% RH was evident
during the period of the eclipse.
- A steady decline in WS was evident just after the onset of the eclipse.
- Pronounced decline in trace gases (ozone and carbon monoxide) was noticed during the
eclipse day. Ozone was decreased by about 10 ppb (40%), with a delay of about 2 hours
  from the peak phase of the eclipse.

Overall, in conclusion, for the first time, our study reported the impact of the solar eclipse on
various meteorological parameters and trace gases measurements at a high-altitude background
station in Taiwan. The observed changes in the meteorological parameters at LABS during the
annular solar eclipse matched well with the previously reported studies (Anderson, 1999; Ratnam
et al., 2010; Nelli et al., 2020). However, compared to the ground-based surface stations (i.e., Naja
and Lal, 1997; Tzanis et al., 2008; Girach et al., 2012; Jain et al., 2020), a higher time lag was
noticed for the maximum drop in the ozone from the full phase of the eclipse. The present reported
measurements at a high altitude background station during the eclipse period further support a
better understanding of the solar eclipse-induced meteorological, dynamic, and photochemical changes in the atmosphere.

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DISCLAIMER

The authors declare no potential conflicts of interest.

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