Lower and middle atmospheric responses to the 22 July 2009 total solar eclipse

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In the present study, the effect of total solar eclipse, occurred on 22 July 2009, on water vapour in the troposphere, refractivity and temperature in the troposphere and the stratosphere using the observations available from COSMIC GPS RO, is reported. The investigation is extended to the entire middle atmosphere using SABER aboard TIMED satellite to study the response in the temperature and ozone. A significant enhancement in the water vapour and the refractivity in the lower and middle troposphere are noticed on the eclipse day when compared to non-eclipse days. Using the GPS RO observations, it is also found that the temperature responds differently at different altitudes, i.e. cooling in the troposphere and warming in the stratosphere. Similar features in temperature are also noticed in SABER observations below 40 km. Above 40 km altitude, cooling is observed up to an altitude of 70 km, therein again warming is noticed. An increase in ozone concentration is found throughout the middle atmosphere except near 30 km. Tropopause altitude is also observed to vary significantly during the solar eclipse with decrease (increase) in the altitude (temperature) of about 1-1.5 km (3-5 K). Large perturbations in the temperature, due to gravity waves in the stratosphere and the mesosphere, are noticed on the eclipse day and found westward propagating as expected. For the first time, evidences of solar eclipse in the entire lower and middle atmosphere is presented using ground based and satellite borne observations.

Keywords: Solar eclipse, Temperature profile, Ozone profile, Radio occultation

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1 Introduction

Middle atmospheric responses to the solar eclipse are now well established through chemical and dynamical changes occurring due to motion of cooling spot with supersonic velocities. Different meteorological parameters respond differently at different heights. Some of them respond quickly and some slowly and rest of them shows only subsequence effects. For example, ozone at stratospheric altitudes responds more quickly than the water vapour in the lower troposphere. Nevertheless, the response of the solar eclipse is expected to be noticed in the ground pressure and temperature, boundary layer height$^1$, upper troposphere and lower stratosphere (UTLS)$^{2,3}$, stratosphere and mesosphere$^4$ in the neutral atmosphere$^5$.

In general, internal waves with periods ranging from few minutes to few tens of hours with horizontal wavelengths of few hundred kilometers are expected to be generated during the solar eclipse$^{6-9}$. Due to easy access to the data, several earlier studies on the effect of solar eclipse concentrated in the troposphere and lower stratosphere. Until recently, temperature changes in the troposphere and the stratosphere during total solar eclipses were studied both by direct measurements and models$^{5,10,11}$. Studies obtained from rocketsonde$^{10}$ and models$^{11}$ do provide convincing influences of solar eclipse, i.e. radiative cooling of the stratosphere. However, no work exists to the best of our knowledge studying the effects of solar eclipse from the surface to 100 km. These studies are lacking particularly over oceanic areas where no measurement is possible from ground-based instruments.

Satellite observations with reasonable accuracies do provide observations over oceanic region; however, it will be very difficult to correlate the effects entirely due to solar eclipse, as their path may not coincide with the eclipse path. Moreover, the vertical resolution and accuracies are poor when compared to ground based observations. Using newly emerged data from Constellation Observing System for Meteorology Ionosphere and Climate (COSMIC) Global Positioning System (GPS) Radio Occultation (RO), which have very high vertical resolution (0.5 km to 1 km) and accuracies (0.5 K) when compared to any other satellite technique$^{12}$, studied
the response of temperature due to 22 July 2009 eclipse. The main conclusions drawn from these studies are: temperature response is different at different altitudes; about 7 K increase in the temperature is noticed around 17 km altitude, and cooling in the troposphere and warming in the stratosphere.

In the present study, the investigation of response of solar eclipse is extended not only to the temperature changes but also on water vapour in the troposphere, temperature and ozone changes starting from near surface to 100 km by combining observations from COSMIC and Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) aboard Thermosphere-Ionosphere-Mesosphere Energetic and Dynamics (TIMED) satellite observations. In addition, the variations observed in the tropopause altitude and temperature, due to solar eclipse using ground based radiosonde observations, are also presented. Finally, signature of the gravity waves in the stratosphere and mesosphere due to eclipse is shown.

2 Data

2.1 COSMIC GPS RO data

COSMIC GPS RO\textsuperscript{13}, a Taiwan and USA joint mission launched on 14 April 2006, consists of six satellites\textsuperscript{14}. The RO provides the profiles of refractivity, pressure, temperature, and water vapour in the lower atmosphere, which are retrieved using inversion techniques. By taking advantage of tracking the signals in both rising and setting occultations, COSMIC provides about 2000 occultations per day across the globe, which is about 10 times larger than earlier CHAMP observations. Additional advantage is the ability to track signals from the lowest altitude regions than other missions since open loop tracking is employed in COSMIC in the lowest 10 km. These six satellites are deployed at an altitude of about 800 km above the Earth’s surface to make radio occultation (RO) observations of the phases of L1 (1575.42 MHz) and L2 (1227.6 MHz) radio waves emitted by the GPS satellites. The self calibration of the observations of the L1 and L2 radio wave phases makes the derivations of the bending angle of the radio waves and the atmospheric index of refraction very accurate\textsuperscript{15}. The accurate radio occultation (RO) observations have a very high vertical resolution and they are nearly unaffected by clouds. Level-2 atmospheric temperature and water vapour profiles obtained from COSMIC website (www.cosmic.ucar.edu) have been used. The accuracy of COSMIC temperature and water vapour is discussed in Rao et al.\textsuperscript{16} and there were 417, 501 and 248 occultations during 21, 22 and 23 July 2009, respectively.

2.2 SABER/TIMED measurements

The SABER instrument aboard TIMED satellite was primarily meant for investigating various atmospheric parameters in the stratosphere, mesosphere and lower thermosphere. The TIMED satellite contains four instruments to study the climatology of the key atmospheric parameters in the height region from the tropopause (~17 km) to lower thermosphere. The kinetic temperature from upper troposphere to lower thermosphere is retrieved from CO\textsubscript{2} limb emission 15 µm using a full non-local thermal equilibrium (non-LTE) inversion\textsuperscript{17,18}. The temperature retrieval uses CO\textsubscript{2} concentration (in version 1.07, level 2A) from Whole Atmosphere Community Climate Model (WACCM) during both daytime and nighttime. SABER processing also retrieves CO\textsubscript{2} concentration during the daytime, but the results from the CO\textsubscript{2} retrieval is not coupled to the temperature retrieval. Also ozone (O\textsubscript{3}) measurements from lower stratosphere to lower thermosphere are used. The TIMED makes ~15 orbits per day at ~ 625 km with an orbital inclination of 74.1\textdegree{} and a period of about 1.6 h, and it takes 60 days to complete full 24 h coverage of local time. For every 58 seconds, SABER provides a profile by scanning up and down the Earth’s horizon. The errors are well documented by Remsberg et al.\textsuperscript{19} and García-Comas et al.\textsuperscript{20}. The retrieval uncertainties in the kinetic temperature are documented by Mertens et al.\textsuperscript{17} and Kutepov et al.\textsuperscript{21}. The retrieval uncertainty was estimated and the values are found to increase from 1.4 K at 80 km to 22.5 K at 110 km. The error in the temperature retrieval is about ~ 4-5 K in the 80-100 km altitude region. A very good comparison between temperatures obtained using the Rayleigh Lidar located at Gadanki and SABER for the height region of ~35-80 km has already been shown\textsuperscript{22}.

2.3 Radiosonde data

It is not possible to study the day-to-day variations from satellite measurements as the over pass/track is not uniform at a given local time, hence, radiosonde observations available over central China are used. The locations of the radiosonde stations along with track of solar eclipse over China are shown in Fig. 1(b). It may be noted that the stations with good data set available are only selected. From Fig. 1, in
general, it can be noticed that solar eclipse path extends from typical extra-tropical (or starting at the mid-latitudes) to equatorial latitudes. The radiosonde stations, where good data is available, have been chosen and these are Wuhan (30.61°N, 114.13°E), Shanghai (31.40°N, 121.46°E), Nanjing (32.00°N, 118.80°E), Nachang (26.68°N, 115.88°E), Hangzhou (30.23°N, 120.16°E) and Chongqing (29.51°N, 106.48°E). For obtaining the background conditions, radiosonde observations for the complete year 2009 available from Wuhan (30.61°N, 114.13°E, 23 m above sea level) Central Station of Meteorology are used on a twice daily basis at 00:00 and 12:00 hrs UTC, which is a typical extra-tropical/mid-latitude station. Location of this station is also shown in Fig. 1(b). As the eclipse path is over ocean in the equatorial latitudes, there is no radiosonde station having good data set, thus, GPS RO data instead is used. It may be noted that 00:00 and 12:00 hrs UTC correspond to 08:00 and 20:00 hrs LT, respectively for Wuhan. The raw data are sampled at 8 sec intervals, resulting in an uneven height resolution, is processed to have an even height resolution of 100 m by applying a linear interpolation. The maximum altitude of radiosonde observation is the burst altitude of the balloon, which on an average is about 85.7% of measurements reached an altitude of 25 km at Wuhan.

3 Results and Discussion

3.1 Background cloud conditions

The daily gridded outgoing long wave radiation (OLR) provided by the NOAA Climate Diagnostics Center website (http://www.cdc.noaa.gov) is used as a proxy for tropical deep convection. Figure 1 shows the latitude and longitude distribution of OLR observed one day before (21 July 2009) and one day after (23 July 2009) including the eclipse day (22 July 2009). Although OLR distribution is shown up to 60°N, the present study is restricted within ±40° only. Deep convection (OLR < 220 W m⁻²) from 20°N to 10°S stretching in southeast direction covering entire longitudinal band of 70-180°E can be noticed on 21 July 2009. There exists another branch of deep convection in between 30°N and 40°N (strictly speaking 45°N) extending 120-160°E stretching in northeast direction. Similar spatial variation in the convection is also noticed on 22 July 2009 with slightly larger (deeper) convection with a small break in the convection in the southeast direction around 120°E and extending the northeast strip still further. Relatively less convective areas are covered on 23 July 2009 when compared to the previous two days, particularly over Indian region although major features remain the same. In general, all the three days show more or less similar features in the spatial distribution of convection. The path for the total solar eclipse at 1-minute resolution taken from NASA website is also shown in Fig. 1(b). The eclipse path started at 00:54 hrs UT, followed by a series of 1-minute longitude-latitude locations tracking the movement of the eclipse from the west to the east, and ended at 04:17 hrs UT. Most of the places are covered by convective areas over the landmass and less/no convection over oceans except in the range of 170-180°E longitudes along the solar eclipse path shown in Fig. 1(b).

Fig. 1 — Latitude-longitude distribution of the outgoing long-wave radiation (OLR) observed during: (a) 21 July 2009, (b) 22 July 2009, and (c) 23 July 2009 [path of the total eclipse showing northern, central and southern limits observed every one minute also superimposed (open circles) in (b); locations of Wuhan and other radiosonde stations along the eclipse path also shown in (b) with filled and open stars, respectively]
3.2 Background meteorological parameters

Before studying the meteorological parameters variations during the eclipse, the mean background conditions expected during that month are shown. Figures 2(a and b) show the monthly averaged zonal and meridional winds over Wuhan during the year 2009. Below the altitude of 3 km, the zonal wind fields are very weak. Within the altitude range of 3–18 km, the zonal winds are eastward and usually increase with altitude up to about 12 km, with maximum values about 70 ms\(^{-1}\) and then decrease with altitude, indicating a strong tropospheric jet around 12 km and show strong annual cycle variation. Above the altitude of 18 km up to 25 km, the zonal wind field is dominated by the annual oscillation rather than the quasi-biennial oscillation observed in tropical latitudes, with a mean flow of \(-5\) to \(10\) ms\(^{-1}\). In general, the westward wind field occurs from June to November, and an eastward wind in the other half of the year. Compared with the zonal wind, the meridional wind is relatively weaker and usually less than 10 ms\(^{-1}\). In the altitude range of 5–20 km, the meridional wind fields are northward in winter and southward in summer. The strongest southward wind often occurs near 15 km altitude in July, the period of present interest, with a maximum value of \(-6\) ms\(^{-1}\). The strongest northward wind occurs at a lower altitude near 11.5 km, with a larger maximum value of 10 ms\(^{-1}\) occurring twice a year in February and November, respectively.

Figure 2(c) shows the monthly averaged temperature observed in the year 2009 in the altitude range from the ground surface to 30 km. The temperatures show large fluctuation with respect to time below the altitude about 14 km with minimum variability above. The tropopause altitude roughly estimated from Fig. 1 is at 17 km altitude. An extremely low temperature less than 195 K around 17 km altitude can be observed more or less representing the tropical behaviour. The coldest temperature above the tropopause occurs in NH summer (June-August), and annual cycles can be observed, although not as regular as they were at the tropical region of Truk\(^{24}\).

Fig. 2 — Time-height cross sections of monthly averaged: (a) zonal wind, (b) meridional wind, and (c) temperature observed during the year 2009 at Wuhan; Time-height cross sections of: (d) zonal wind, (e) meridional wind, and (f) temperature observed twice daily during 17-27 July 2009 [highlighted box denotes the solar eclipse month and day in the left and right panels, respectively]
More detailed background meteorological parameters few days before and after the solar eclipse are shown in Figs 2(d-f). Weak eastward winds below 15 km are expected during the month of July [Fig. 2(a)], and there is no big change during and after the eclipse day although westward winds dominate few days before. Meridional winds are expected to be southward between 10 and 20 km; however, large day-to-day variation is seen in Fig. 2(e). A slight increase in tropopause temperatures is noticed after the solar eclipse [Fig. 2(f)].

3.3 Cold point tropopause variations

The tropopause variations during the eclipse are also studied using ground based radiosonde observations. Before studying the tropopause variations during the eclipse, the monthly variation of tropopause altitude and temperature over Wuhan is shown in Fig. 3(a). One can notice annual variation in the tropopause altitude with maximum (minimum) during NH winter (summer). A clear mirror image in the temperatures can be noticed. It is noted that mean tropopause altitude (temperature) during July (eclipse) month is 17.40±0.58 km (195.28±2.79 K). Tropopause altitude is in transition from typical NH winter to summer in the July month. This behaviour is more or less same at other stations (figure not shown). Detailed variations in the tropopause altitude and temperature one day before and after the solar eclipse observed at all the locations mentioned are shown in Figs 3(b and c), respectively. Interestingly, the tropopause altitude is observed at 17.5 km one day before and after at all the stations representing as a typical for that month and a clear decrease in the altitude of tropopause of about 1-1.5 km can be noticed with increase in temperature of about 3-4 K on the eclipse day at 00:00 hrs UTC. Although the launch time at Wuhan corresponds to 08:00 hrs LT and eclipse time is around 09:30 hrs LT, it takes about one and half hour for the balloon to reach the tropopause height, which exactly coincides with the eclipse time. This feature is clearly observed in Wuhan, Nachang, and at 12:00 hrs UTC at Nanjing and Hangzhou. Surprisingly, Chongqing did not show

Fig. 3 — (a) Monthly mean variation of tropopause height and temperature observed using radiosonde data from Wuhan.
such feature although located along the track of eclipse. Conversely, increase in the tropopause altitude at 00:00 hrs UTC is noticed at Shanghai although decrease in the altitude is reproduced well in Nanjing and Hangzhou stations.

4 Variations observed in profiles of N, T and RH in GPS RO measurements

It is well known that the influence of solar eclipse will be different at different altitudes due to various concentrations of chemical species, which in turn get affected differently at different altitudes. In order to study the effect of solar eclipse on the meteorological parameters at different altitudes, the profiles of refractivity (N), temperature (T) and relative humidity (RH) from the COSMIC GPS RO measurements in the vicinity of the eclipse track are used. Figure 4(a-c) shows the locations (green dots) where occultations (averaged location between 40 km and near surface) have occurred during 21-23 July 2009, respectively. As the occultations are not uniformly distributed, a challenging task exists in the proper selection of the profiles which otherwise contaminate entire results. For the selection of profiles, the procedure adopted by Wang & Liu\textsuperscript{12} is closely followed. The major difference, between the present study and Wang & Liu\textsuperscript{12}, is usage of direct refractivity profiles rather than only temperature, showing the water vapour variations during the eclipse in addition to variations in the temperature and ozone from 20 km to 110 km using SABER observations.

In brief, for each 1-minute eclipse location, search for COSMIC GPS RO profiles that had occurred within a 3-hours time window (1.5 hours before and after the passage of the eclipse) is made. The 1.5 hours in time corresponds to an approximately 2250 km distance in space (3-hours time difference corresponds approximately to 45° difference in longitudes, for latitudes averaged between 30°N and the equator). It is to be noted that the 2250 km radius accounts for the spatial coverage of area with totality of eclipse that is greater than 30\% (Ref. 23). Wang & Liu\textsuperscript{12} already tested and found that the prominent eclipse effects are maintained when the distance

![Spatial distribution of occultations observed using COSMIC GPS RO during: (a) 21 July 2009, (b) 22 July 2009, and (c) 23 July 2009; Spatial distribution of occultations observed using SABER during: (d) 21 July 2009, (e) 22 July 2009, and (f) 23 July 2009 [path of total eclipse showing northern, central and southern limits observed every one minute also superimposed (open circles) in (b) and (e); occultations/overpass observed in a complete day, within ±10° from center point of solar eclipse, and with in ± 1.5 hours shown in green, red, and blue circles, respectively]
(2250 km) and time (3-hours) is greater or smaller than these threshold values. It may be noted that smaller threshold values give fewer GPS profiles for analysis, while larger threshold values contain more GPS profiles that are less influenced by the eclipse passage. The red dots indicate the GPS RO profiles which are located within 2250 km radius of distance from the center of the eclipse location without considering the timing of the occurrence of these profiles. The blue dots indicate GPS RO profiles that are located within a 3-hour time window along the 1-minute resolution eclipse path in addition to considering the spatial distance of these profiles to the eclipse path. Only those GPS RO profiles that are close enough in space (within 2250 km radius) and near enough in time (within 3-hour time window) are chosen for analysis.

The daily GPS RO profiles found along the eclipse path with 2250 km spatial radius and 3-hour time window are averaged for 22 July 2009. In order to compare the daily GPS RO profiles with the effect of the solar eclipse to those daily GPS RO profiles without the influence of the solar eclipse, the same eclipse path, time window, and spatial radius 10 days before (started from 12 July) and after 22 July (ended on 1 August), respectively are applied in the present study, as was done by Wang & Liu\textsuperscript{12}. The main aim for doing so is to compare the results, which are common while emphasizing on the variations in refractivity and water vapour.

Daily mean profiles of GPS RO refractivity, temperature, and relative humidity (RH) observed for five days before and after including the eclipse day are shown in Figs 5(a-c), respectively. An enhancement in the refractivity with gradual decrease up to 10 km, a sudden decrease in temperatures near the tropopause, an increase in relative humidity can be clearly noticed on the eclipse day. The lower temperatures below 13 km and higher temperatures near tropopause and above on the eclipse day are also found when compared to few days before and after the eclipse. To show the features in detail, daily mean profiles are used and the difference between the profiles observed on eclipse day and each non-eclipse day is estimated and shown as time-height cross sections in Figs 5(d-f) and as difference profiles in Figs 5(g-i). Figure 5(g) reveals a consistent enhancement in the refractivity with gradual decrease up to 10 km and again enhancement of about 2.5 N units between 10 and 20 km on eclipse day when compared to non-eclipse days. The differences in temperature at altitudes below 13 km are consistently negative, while temperature differences at altitudes between 13 and 23 km (upper troposphere

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Fig_5.png}
\caption{(a-c) Profiles of daily mean: (a) refractivity, (b) temperature, and (c) relative humidity observed by COSMIC GPS RO during 17-27 July 2009; (d-f) Time-height cross sections of the observed differences between the solar eclipse day and the non-eclipse days; Profiles of the observed differences in: (g) refractivity, (h) temperature, and (i) relative humidity.}
\end{figure}
and lower stratosphere) are positive. Temperature differences at altitudes between 23 and 30 km are positive. The negative differences in temperature indicate that temperatures measured on the eclipse day (22 July) are lower than each day of 5 days before and after the eclipse. On the other hand, the positive differences in temperature indicate that temperatures during the eclipse are higher than those non-eclipse days. The averaged daily temperature difference with respect to 22 July is less than 5 K at 1 km; and then reduced to the values between 5 and 3 K from 3 to 13 km. The averaged daily temperature difference becomes positive above 13 km, which exhibit a sharp increase to peak at about 7 K at 17 km altitude. It then reduces in strength but remain positive as the altitudes go higher from 13 to 30 km altitude. About 10-20% enhancement in the relative humidity can be noticed on the eclipse day from 2 to 9 km [Fig. 5(i)].

It may be noted that difference in the refractivity and the temperature between the eclipse day and the days just after (23-24 July 2009) seem to be smaller, which can be clearly observed from Fig. 5(g) and Fig. 5(h), respectively. This could imply some persistence of the eclipse effects during the following few days. In summary, it is found that during the total solar eclipse, the troposphere is on an average cooled by about 2 K, while the stratosphere is warmed with a mean maximum warming of 7 K at 17 km altitude, an increase of about 2.5 N units and 10-20% increase in the relative humidity.

5 Variations observed in profiles of temperature (T) and ozone (O₃) in SABER measurements

From Fig. 5, it is clear that the temperature difference at altitudes between 23 and 30 km are predominantly positive. It may be noted that GPS RO does not have accurate data above 35-40 km due to uncertainty (due to increase in ionospheric influence) in the retrieval technique. Thus, as mentioned earlier, SABER measurements are used to study the effect of eclipse on temperature at 30 km and above.

It may be noted that SABER employs completely different technique than GPS RO. Figures 4(d-f) shows the locations (green dots) where overpass have occurred during 21-23 July 2009, respectively. Unlike GPS RO, SABER has both ascending and descending nodes on the same day. This data is very much useful to study the effects during and after the eclipse on the same day. The red dots indicate the SABER overpasses which are located within a 2250 km radius of distance from the center of the eclipse location without considering the timing of the occurrence of these overpasses. The blue dots indicate overpasses that are located within a 3-hour time window along

![Fig. 6 — Profiles of daily mean: (a) temperature and (b) ozone observed by SABER during 12-31 July 2009; Time height cross sections of the observed differences between the eclipse day and the non-eclipse day in the daily mean of: (c) temperature and (d) ozone; Profiles of daily mean differences: (e) temperature and (f) ozone](image-url)
the 1-minute resolution eclipse path in addition to considering the spatial distance of these overpasses profiles to the eclipse path. Only those overpasses that are close enough in space (within 2250 km radius) and near enough in time (within 3-hour time window) are again chosen for analysis.

Time-height cross sections of difference between the profiles observed on eclipse day and each non-eclipse day in temperature and ozone are shown in Fig. 6. Interestingly, the increase in temperature from 20 to 40 km is again noticed in the SABER measurements although less in the amplitudes. Thereafter, there is a decrease in temperature more consistently between 55 and 70 km. Between 70 and 90 km, there is again increase in the temperatures, however, not consistently observed. Although uncertainty in measuring the temperature above 100 km is high, very large increase in the temperature is noticed above the mesopause (~100 km).

Time-height cross sections of difference between the profiles observed on eclipse day and each non-eclipse day in ozone is shown in Fig. 6(b). A consistent increase in ozone can be noticed between 20 and 90 km except near 30 km. A decrease in ozone is seen above 90 km.

6 Variations in the temperature along the path (longitudinal variation)

The temperature variations on the eclipse day and non-eclipse days are discussed above by considering all the occultations/profiles in the vicinity of the eclipse path without considering their locations while dealing before and after the eclipse effects. The variability in the temperature is shown by considering only those profiles which occurred within ±3° latitude and longitude separation and ±3 hours in time on the eclipse day to the previous and after the eclipse. This exercise will help in dealing the effect of solar eclipse more precisely. Figure 7(a and b) shows the profiles of temperature observed on the eclipse day and previous day, eclipse day and next day, respectively, sorted according to the longitude. A clear decrease and increase in the temperature below and above 13-14 km, respectively, can be noticed from Fig. 7(a), i.e. between eclipse day and previous day. The decrease and increase in the temperature is rather small between eclipse day and next day [Fig. 7(b)]. Relatively larger perturbations in the profiles can be noticed on the eclipse day profiles, which may be due to gravity wave generation. It is well known that gravity waves are actively generated due to motion of cooling spot with supersonic speeds.  

Fig. 7 — Profiles of temperature observed on the eclipse day (solid line) and: (a) previous day (21 July 2009); and (b) next day (23 July 2009) sorted according to the longitude [each profile shifted with 10 K]
Gravity wave features are more visible in the profiles of temperature shown in Fig. 8(a) observed using SABER measurements on the eclipse day. It may be noted that profiles observed on the previous day and next day do not show any systematic features. However, a clear downward phase progression with respect to longitude is noticed on the eclipse day with vertical wavelengths of 10-12 km suggesting the westward progression of disturbances. This feature is quite expected as eclipse path is moving towards east; the disturbances propagate towards west providing strong support that these disturbances are due to wave generation due to eclipse. Profiles of ozone shown in the similar way, however, do not show pronounced variations as that of temperature profiles.

7 Summary and Conclusions
The influence of solar eclipse occurred on 22 July 2009 on the profiles of temperature, water vapour, and refractivity below 40 km using COSMIC GPS RO measurements and on the temperature and ozone in the entire middle atmosphere (20-100 km) using SABER data are investigated in the present work. Main findings are summarized as:

i. Response of the solar eclipse in the temperature is observed differently at different altitudes using COSMIC GPS RO. A strong cooling (~5 K) in the troposphere and warming (~7 K near 17 km and 3-4 K above) in the stratosphere is noticed on the eclipse day when compared to non-eclipse days.

ii. A consistent increase in relative humidity of about 20% is noticed on the eclipse day.

iii. The combined effects of temperature and water vapour due to eclipse are clearly noticed in the profiles of N of COSMIC GPS RO. A large enhancement (10-20 N units) in N in the lower troposphere and about 2.5 N units near the tropopause is noticed.

iv. A decrease (increase) in the tropopause altitude (temperature) of about 1-1.5 km (3-4 K) is clearly observed on the eclipse day from radiosonde observations.

v. No change in the zonal and meridional wind is observed during or after the eclipse day.

vi. Warming in the stratosphere is again noticed in the SABER measurements below 40 km although amplitudes are less (2-3 K) when compared to COSMIC GPS RO observations. However, cooling is noticed above 40 km with strong cooling (~5 K) between 60 and 70 km. There exists strong warming (~5 K) between 70
and 90 km and strongest cooling near the mesopause (~97-98 km).

vii. A consistent enhancement in the ozone is noticed throughout the middle atmosphere except near 30 km where reduction is observed.

viii. A clear signature of wave generation is noticed on the eclipse day particularly in the mesosphere, which is observed to be westward propagating.

Since no big difference in the background convection exists between the eclipse day and non-eclipse days (Fig. 1), all the changes mentioned above are attributed to eclipse. As also mentioned by Wang & Liu, the net cooling in the troposphere (Fig. 5) may be attributed to the reduction in solar heating and this cooling in turn may produce contraction in the middle to lower troposphere, which induces downward movement in the upper troposphere and lower stratosphere resulting in the warming of that region. This aspect is clearly seen in the tropopause height coming down by 1-1.5 km with temperature increase of about 3-4 K (Fig. 3). It is also found that response of eclipse on the tropopause altitude is different depending on the location of site whether far inland, coastal, or in the oceans. Far inland stations showed immediate response with larger intensity than coastal stations and minimum in oceanic regions. The difference in the temperature between the eclipse day and the previous day is large when compared to eclipse day and next day (Fig. 6), which may be due to subsequent effects persisting for few days. Large perturbation in the temperature throughout the middle atmosphere on the eclipse day (Fig. 7) is noticed relatively to the non-eclipse days perhaps due to gravity wave generation. Although no direct effects on the ozone due to eclipse in the stratosphere is expected as the life time of ozone is large (3-4 months), consistent enhancement in the ozone noticed throughout the middle atmosphere, which may be attributed to the dynamical effects due to waves. Mathematically, it was shown that internal gravity wave motions are generated in the earth’s atmosphere during a solar eclipse. These waves, which would produce a bow waves, are believed to be generated by moons screening of the ozone UV absorption in the stratosphere. Since generation of these waves is mainly located at middle stratospheric altitudes, these waves will propagate both upward and downward from the source region. It may be noted that the waves generated in the stratospheric altitudes have to propagate through higher density medium down below; hence, amplitude will be small, although some evidence is there from Fig. 7. However, the waves propagating upward into upper stratosphere and mesosphere can be effectively detected, as the amplitudes will be large as shown in Fig. 8. Nevertheless, the second set of waves generated at higher altitudes and lower altitudes (due to response of water vapour) cannot be ruled out.

Since these bow waves are detectable at greater distances from the eclipse path, and eclipse that occurred on 22 July 2009 is ideal to detect these waves, further work will be focused on the detection of the waves using ground based instruments located around Indonesian region. Most of the mechanisms for the observed results are explained qualitatively. Similar analysis for the recent eclipse that occurred on 15 January 2010 using the satellite observations, starting from surface to the complete middle atmosphere, is in progress.

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