LETTER

Radiation profiles from the surface up to the upper troposphere and lower stratosphere over the Tibetan Plateau

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Abstract

Variations in solar shortwave and thermal longwave radiation over the Tibetan Plateau (TP) are crucial for global climate and regional ecological environment. Previous radiation studies over the TP were widely based on ground and satellite measurements of the radiation budget at the surface and at the top of the atmosphere. A stratospheric balloon-based radiation measurement system was employed in a 2019 field campaign to study how and why radiation profiles vary over the TP during the Asian summer monsoon (ASM) period. We originally provide in situ measurements of multiwavelength radiation profiles from the surface up to the upper troposphere and lower stratosphere (UTLS) over the TP. These valuable observations, combined with simultaneous operational radiosondes, ground measurements, satellite retrievals and radiative transfer model simulations, are used to study radiation variations and the radiative forcings of clouds and aerosols over the TP during the ASM period. Cloud occurrences beneath the balloon flight altitude induce more balloon-borne shortwave upward radiation and ultraviolet upward radiation but less longwave upward radiation relative to clear sky counterparts. The radiative transfer model simulations capture the variations in balloon shortwave downward radiation (SDR) profiles well. Cloud radiative forcings at the UTLS and surface vary greatly with varying cloud cover. The diurnal evolution of the SDR discrepancy between the balloon altitudes and surface and the aerosol radiative forcing at the bottom of the atmosphere are also discussed during the balloon flight periods. The results of this study are expected to improve our understanding of radiation properties in the UTLS and help us better comprehend the thermal conditions associated with clouds and aerosols over the TP during the ASM.

1. Introduction

Variations in the radiation budget can profoundly affect the terrestrial environment (Wild et al. 2005). Accurate comprehension of radiation properties is valuable in addressing a variety of scientific and application issues, such as climate change, land surface modeling, solar energy, and stratospheric ozone change (Haigh et al. 2010, Zhang et al. 2020a). The solar flux reaching the surface is highly variable at both temporal and spatial scales (Dahlback et al. 2007, Xia 2010, Yang et al. 2016, Gueymard 2017), since it is subject to scattering and absorption by atmospheric gases (such as water vapor, ozone, etc.), aerosols, cloud particles, and surface properties (altitude, gradient, slope direction and surface albedo) (de Miguel et al. 2011, Bauer and Menon 2012, Yu et al. 2020). Many approaches have been proposed to estimate the radiation budget. Surface measurements from the Baseline Surface Radiation Network (BSRN) of the World Climate Research Program have been available since 1992.
(Ohmura et al. 1998). This network provides surface radiative fluxes at the highest possible accuracy because its instrumentation are well calibrated and can provide measurements continuously. However, ground-based instruments are incapable of providing information about radiation properties on the global scale due to their scarce distributions. Space-borne satellite data (Pinker et al. 2005, Stephens et al. 2012) and model simulations (Pinty et al. 2004, Xie et al. 2013) are also widely used to analyze the radiation budget at both surface and top of the atmosphere. Although satellite measurements and model simulations can provide a vital dataset for understanding the properties of global radiation, they are usually subject to retrieval uncertainties and need to be substantially improved through comparison with ground-based measurements. A few studies have attempted to use a weather balloon (Philipona et al. 2012, Kräuchi et al. 2016) and return glider radiosondes (Kräuchi and Philipona 2016) to measure the radiation profile in the atmosphere, in which the horizontal attitude control of the instruments should be fundamental to collecting accurate measurements.

The Tibetan Plateau (TP), as the highest (average elevation >4 km above sea level: ASL) and broad (∼2.5 × 10⁶ km²) plateau in the world, significantly influences the regional weather and climate of the Northern Hemisphere through its unique thermal and dynamical forcings (Wu et al. 2007, Yao et al. 2012). The Asian summer monsoon (ASM) anticyclone, existing from May–June to August–September every year, is a dominant circulation system in the upper troposphere and lower stratosphere (UTLS) over the TP in the summer seasons (Yanai et al. 1992, Ueda and Yasunari 1998). Previous studies indicated that the ASM may effectively transport tropospheric air into the stratosphere by creating a dome or ‘bubble’ of tropospheric air above the zonal mean tropopause (Randel et al. 2010, Vernier et al. 2015, Yu et al. 2017). The function as an ‘air pump’ should be particularly prominent on the TP since it is located in the core region of the ASM (Fu et al. 2006) and is characterized by strong solar radiation heating on its high massive ‘mesa’ in boreal summer (Xu et al. 2014). Previous studies also suggested that the radiative heating pump effect of the TP might affect the aerosol transport from India, particularly those absorbing aerosols, which can further affect the heating pump effect, along with those cloud-associated processes (Wu et al. 2007, Lau et al. 2018, Zhao et al. 2020).

A detailed understanding of radiation properties over the TP will help us better comprehend the thermal processes of pollutant transportation by the ASM into the stratosphere. Previous radiation studies over the TP were widely based on satellite measurements (e.g. Yang et al. 2008, Wang and Liang 2009), which are indicated to be unable to meet the requirements of research communities well (Gui et al. 2010, Shi et al. 2018). Given the great challenge and high expense of conducting field campaigns on the TP, surface measurements with high accuracy and temporal resolution are quite scarce over this unique geographical area. More importantly, to the best of our knowledge, in situ vertical radiation measurements across the UTLS have not been ever reported over the TP or even over a large territory of China, which is likely associated with difficulty in performing such measurements.

As part of a five-year (2018–2022) stratosphere-troposphere exchange experiment during the ASM project, high-quality radiometers were released twice by stratospheric balloons at Qaidam (QDM) during the 2019 ASM period to provide radiation profiles from the surface to the UTLS over the TP. The direct in situ observations of radiation will significantly reduce some limitations of the temporal and vertical resolutions of satellite data and aid in better understanding the ASM thermal processes that vent tropospheric aerosols up into the stratosphere. Additionally, for the first time, this study provides in situ vertical radiation measurements across the UTLS over China. Moreover, continuous ground-based radiation and aerosol measurements and intensive radiosonde launches were also performed during the campaign. Based on these comprehensive observational datasets and the synergy of satellite measurements and model simulations, this study aims to analyze the radiation properties and discuss the radiative forcings of clouds and aerosols over the TP during the ASM. The paper is organized as follows: section 2 briefly describes the site, measurements and model simulations. The main results are presented in section 3, and a conclusion is given in section 4. An appendix is also attached to explain the details about the measurements used in this study.

2. Site, measurements and model simulations

2.1. Site
We conducted a field campaign at QDM (37.74°N, 95.34°E; 3188 m ASL) from 14 July to 30 August 2019. Beijing (BJ) time is used throughout the paper. As shown in figure 1, QDM, in the hinterland of the TP, has an inland plateau desert climate. The QDM is located in the northwestern Qinghai Province and the northern margin of the QDM Basin. Northwesterly wind dominates the site, with an annual maximum wind speed of ~20 m s⁻¹, which may result in frequent occurrences of dust at the QDM. The average annual temperature and precipitation are 1.4 °C and 83.5 mm, respectively.

2.2. Measurements
Six radiometers aboard the stratospheric balloon were used to provide downwelling and upwelling radiations, i.e. shortwave downward radiation (SDR),
2.3. Model simulations
The Santa Barbara DISORT Atmospheric Radiative Transfer (SBDART) program, as a software tool designed for computing plane-parallel radiative transfer within the Earth’s atmosphere and at the surface (Ricchiazzi et al 1998), is used in this study to simulate solar radiation (SDR and SUR) at stratospheric balloon flight altitudes and at the surface during balloon flight periods. SBDART is developed based on a series of reliable physical models and is widely used to simulate atmospheric radiative energy in satellite remote sensing and atmospheric radiation budget studies (e.g. Bibi et al 2017, Zhao et al 2019). The parameter settings used in this study are defined as follows. The solar spectrum range is set from 0.285 to 3 \( \mu \)m to match the spectral range of the shortwave radiometer we used, and the spectral interval is 0.01 \( \mu \)m. The surface albedo as input is measured by a ground-based four-component radiometer (MR-60). Aerosol properties (AOD, single scattering albedo and asymmetry factor) and visibility are provided by sunphotometer and local weather observations. Except for the profiles of water vapor and ozone from the intensive radiosonde and ozonesonde measurements, the other parameters are from the standard atmospheric profile of mid-latitude summer. Since we had considered the major components (surface albedo, aerosol properties, water vapor and ozone profiles) that have a distinct influence on broadband direct irradiance, the bias induced by the use of standard atmospheric profile should have little influence on our simulations (Aruna et al 2016). No clouds are assumed in the simulation to derive the clear-sky radiation. Solar zenith and azimuth angles, elevation and
surface altitude corresponding to the balloon-borne irradiance simulation are calculated according to the latitude, longitude, and time of each instantaneous balloon measurement. For unspecified parameters, default values are applied.

3. Results

3.1. Background meteorology

To understand the large-scale synoptic circulations and facilitate the radiation analysis in subsequent sections, figure 2 shows the meteorological conditions at 500 hPa from the ERA5 reanalysis. On July 23, the QDM was located in the rear of a high-level trough, and there was a northwesterly flow at the 500 hPa level associated with strong divergence and descending motion in the low atmosphere. Clear skies or scattered clouds dominated, followed by shallow convective clouds which developed in the afternoon. On August 16, the QDM was located in front of the upper trough, and a south flow at the 500 hPa level was associated with strong convergence and ascending motion in the low troposphere; cloudy skies prevailed. On August 17, a ridge of high pressure dominated the QDM at the 500 hPa level and was associated with strong convergence and descending motion in the upper atmosphere. Clear skies dominated. The geopotential height at the 150 hPa pressure level, which is commonly used to approximately denote the boundary of the ASM anticyclone, indicated that the QDM was generally located in the northern ASM region during the two flight periods (Zhang et al 2020b).

3.2. Flight 1: July 23, 2019

Figure 3 shows the radiation evolution from the first balloon measurements on July 23. Temporally collocated ground-based radiation measurements are also presented for comparison. To differentiate these two types of measurements, the subscripts for the balloon and surface are set as ‘b’ and ‘s’, respectively; for instance, SDR$_b$ and SDR$_s$ represent the SDR from the balloon and surface measurements, respectively. Overall, a similar varying pattern was presented by the balloon-borne SDR and UVDR, which was also similar for balloon-borne SUR and UVUR (figures 3(a) and (b)). From 06:00 to 10:00, the weather was clear sky, as shown by the smooth variation tendency of the surface SDR; the discrepancy between the balloon and surface measurements increased with the ascending periods due to the absorption and scattering by gases and aerosols in the atmosphere. The dramatic variation in surface SDR after ~10:00 suggested that scattered clouds occurred and were maintained to the end of the balloon flight, which was also clearly exhibited by the MODIS RGB image in the afternoon (figure 4(a)). No cloud layer was retrieved from the radiosonde measurements in the early morning (figure 4(b)). In the afternoon, much more moisture accumulated in the middle troposphere where a cloud layer formed at approximately 9–10 km (figure 4(c)). The cloud distribution is roughly presented here for better understanding of the varying radiation features, whereas a quantitative assessment of the cloud radiative forcing (CRF) is performed in the following section.

CALIOP measurements indicated a discontinuous aerosol layer suspended at 5–9 km (figures 4(d) and (e)), which contained multiple aerosol types, such as smoke, clean continental, polluted dust (dust and smoke), dust, and dusty marine (mixtures of dust and marine aerosol). The daily average AOD440 and ARF retrieved from the sunphotometer were 0.14 and ~41.3 W m$^{-2}$, respectively. Several years of CALIOP measurements indicated that the aerosol loading was generally low (AOD < 0.2 at 532 nm) in the main body of TP in each season (Zhang et al 2018), which was influenced by the transport of aerosols from surrounding areas (Huang et al 2007). Due to the combined radiative forcing of clouds and aerosols, the discrepancy between the surface and balloon measurements increased after 10:00, with a difference of 160 W m$^{-2}$ for SDR and 17 W m$^{-2}$ for UVDR at 14:00 (figures 3(a) and (b)). The balloon-borne SUR and UVUR showed very similar varying zigzag manners between 11:00 and 16:00, which should be primarily associated with variations in the solar radiation reflected by varying cloud amounts. Due to the higher albedo of the cloud than the surface, the balloon SUR was much larger than the surface SUR, with a maximum difference of 260 W m$^{-2}$ at 15:00 associated with the variations in cloud cover and diurnal SDR evolution.

A faster decreasing rate was presented by the balloon LUR than the balloon LDR during the ascending periods (figure 3(c)). During the level flight at approximately 21 km, the LUR showed more drastic changes than the LDR. This difference occurred because the overwhelming majority of air mass, aerosols and clouds were distributed below the UTLS; their diurnal variation in the thermal state plus infrared emission from the Earth’s surface will significantly influence the balloon LUR. In contrast, the balloon LDR is relatively stable due to the small fraction of air mass above the balloon. The balloon LUR (LDR) varied in the vicinity of 250 (150) W m$^{-2}$ at approximately noontime, which was approximately half of the surface LUR (LDR). Additionally, the balloon LUR and surface LDR, both of which are largely emitted by clouds, were relatively close. As mentioned earlier, the balloon SUR and UVUR showed similar zigzag variations between 11:00 and 16:00; their maximum magnitudes were 537.3 and 32.5 W m$^{-2}$, respectively, at 15:40 when the lowest LUR (215.4 W m$^{-2}$) occurred. The cloud beneath the balloon can reflect downward solar radiation, emit thermal infrared radiation, and block upward thermal infrared radiation from the surface, whereas the emissivity of clouds is generally smaller than...
that of the blackbody surface. The above combined effects of clouds will result in enhanced balloon SUR (UVUR) and reduced balloon LUR relative to clear sky counterparts.

3.3. Flight 2: August 16–17, 2019

The radiation profile collected during the second balloon flight is shown in figure 5. Compared with the first flight, the balloon SDR and UVDR on the second flight were less by 24.5 and 2.9 Wm\(^{-2}\), respectively, at 14:00 due to the increase in the solar zenith angle. Again, similar varying structures between balloon SDR (SUR) and UVDR (UVUR) were presented on the second flight (figures 5(a) and (b)) under both weather conditions with large cloud cover (August 16) and quasi-clear sky (August 17), as shown by the scattered manner of the surface SDR and UVDR. MODIS RGB images also demonstrated evident discrepancies in cloud distributions between the two flight days (figures 6(a) and (b)). Three radiosondes, which were launched in the late morning, noon and late afternoon on August 16, displaced a persistent cloud layer that existed in the middle troposphere throughout the day (figures 6(e)–(g)). A gradual cloud dissipation pattern was also revealed by the decreasing cloud thickness during the three periods. The maximum balloon SUR (UVUR) was 640.4 (38.6) Wm\(^{-2}\) at 13:12 August 16 when the least LUR (228.3 Wm\(^{-2}\)) synchronously occurred (figure 5(c)). A closer look indicated that this point-in-time corresponded to the largest cloud cover, as shown by the least magnitude of surface SDR and UVDR. Sunphotometer retrievals were unavailable on August 16 due to cloud contamination. The daily average AOD440 and ARF from the sunphotometer were 0.11 and \(-31.4\) Wm\(^{-2}\), respectively, on August 17. CALIOP determined one thick aerosol layer in the middle troposphere and one thin aerosol layer around the thermodynamic tropopause in the early morning on August 17 (figures 6(c) and (d)). The bottom-layer
aerosols at 4–7 km were mainly composed of polluted dust, dust, smoke, polluted continental/smoke, and clean continental. Previous studies have confirmed an aerosol layer in the UTLS over ASM regions, namely, the Asian tropopause aerosol layer (ATAL), which is likely to generate an important radiative forcing on the regional and even global atmosphere (e.g. Vernier et al 2015, Yu et al 2017). CALIOP measurements on August 17 suggested an ATAL (i.e. the aerosol layer around the thermodynamic tropopause) composed of smoke and polluted dust. This ATAL has also been recorded by a balloon-borne portable optical particle counter which measures aerosol particles between approximately 120 and 3400 nm in diameter using single-particle light scattering (Zhang et al 2020b).

A further study based on these comprehensive measurements and model simulations is still needed to solely elucidate the radiative forcing of this enhanced ATAL in the UTLS. The quasi-clear sky on August 17 resulted in relatively smooth variations in downward and upward shortwave and UV radiation from both balloon and surface measurements (figures 5a and b).

The balloon flight through the day and night allows us to analyze the diurnal variation in thermal infrared radiation at the UTLS. The LDR and LUR from both balloon and surface measurements exhibited a uniform decreasing pattern after sunset (figure 5c). At a more detailed level, compared with the surface LDR, the balloon LDR tended to decrease much more from sunset to midnight and increase much faster after sunrise. In general, the LUR from the balloon and surface presented a similar diurnal variation pattern.

3.4. Comparison of measurements and simulations

The solar radiations (SDR and SUR) from balloon measurements (SDRb and SURb) and model simulations at the balloon flight attitude (SDRbM and SURbM) during the first flight on 23 July are shown in figure 7; the surface measurements (SDRs and SURs) are also presented given that their variation can well exhibit cloud occurrence. Good agreement was exhibited between the SDR from the balloon measurements and model simulations, as shown by their highly overlapping profiles (figure 7a). Their correlation coefficient (R), mean bias error (MBE; SDRb − SDRbM), and root mean square error (RMSE) were 0.99, 4.6 W m$^{-2}$, and 12.6 W m$^{-2}$, respectively. These results suggested that, by correctly inputting the major components (surface albedo, aerosol properties, water vapor and ozone profiles) derived from field observations with high accuracy, the radiative transfer model indicated reasonable reliability in simulating radiation profiles over the TP. The SDR comparison between the balloon measurements and simulations was not affected by cloud occurrence below the balloon flight altitude. The measured and simulated SUR values at the balloon flight attitude generally agreed under clear sky conditions (figure 7b). To analyze the CRF (defined as the difference between each instantaneous
measurement and retrieval under clear sky conditions), we simulate the solar radiations under clear sky conditions by assuming no clouds in the radiative transfer model, which is deemed to be clear-sky radiation in this study. Compared with the model simulations, a much larger SUR was displayed by the
Figure 7. (a) SDR from balloon measurements (SDR_b; colored line), model simulations at the balloon flight altitude (SDR_M; black line marked by dots on the hour), and surface measurements (SDR_s; gray dots). (b) Similar to (a) but for SUR. The color bar used for the balloon measurements in panels (a)–(b) represents the flight altitude of the stratospheric balloon. (c) Surface SDR from ground-based measurements (SDR_s; gray dots), model simulations (SDR_M; blue line) and fitting method (SDR_F; red line) under a clear sky. (d) Surface SUR from ground-based measurements (SUR_s; gray dots) and model simulations (SUR_M; blue line) under a clear sky.

Figure 8. Similar to figure 7 but for solar radiation on 16–17 August 2019.
balloon measurements under a cloudy sky due to cloud reflection. The maximum CRF on the balloon SUR (SUR$_{b}$ − SUR$_{b}M$) was 278.4 Wm$^{-2}$ at 15:40; the average CRF on the balloon SUR was 51.3 Wm$^{-2}$ after clouds occurred at 10:00.

The surface solar radiations from ground-based measurements (SDRs and SURs) and model simulations under a clear sky (SDRsM and SURsM) are shown in figures 7(c) and (d). To compare with the simulated SDRsM values, the fitting method of Long and Ackerman (2000) based on an empirical formula ($a \times \mu^b$) was applied to the SDRs to derive surface fitting SDR under a clear sky (SDRsF), where $\mu$ is the cosine of the solar zenith angle, and $a$ and $b$ are the fitted coefficients. Consistent variations were exhibited among SDRs, SDRsM, and SDRsF before 10:00 under clear sky conditions (figure 7(c)). After 10:00 under cloudy sky conditions, obvious discrepancies existed between the surface measurements and the other two retrievals under clear sky conditions (SDRsM and SDRsF). The surface SDR is theoretically composed of direct normal irradiance and diffuse solar irradiance. Compared with the retrievals under a clear sky, much less surface SDR is detected when direct normal irradiance is blocked by clouds on the radiometer line to the sun, whereas larger surface SDR is observed when diffuse solar irradiance is emitted by an inhomogeneous distribution of broken clouds out of the radiometer line to the sun. Overall, the two retrievals under a clear sky agreed well, despite slight differences around noontime. Similar to the SDR comparison, the measured and simulated surface SUR agreed under clear sky conditions, in contrast with the large difference after cloud formation (figure 7(d)). The CRFs on the surface SDR and SUR are defined as SDRs − SDRsM and SURs − SURsM, respectively. A positive or negative sign of the SDRs − SDRsM indicates a heating or cooling effect, respectively, on the surface, whereas it is the opposite for the SURs − SURsM. The positive CRF values on the surface SDR and SUR were 237.4 and 44.1 Wm$^{-2}$ at most, respectively, at 16:12. The peak negative CRF on the surface SDR and SUR were −836.3 and −252.3 Wm$^{-2}$, respectively, at 14:03. The daily average CRFs on the surface SDR and SUR were 7.8 and −20.1 Wm$^{-2}$, respectively, leaving a net warming effect of surface shortwave radiation (27.9 Wm$^{-2}$).

The solar radiation from the second flight on 16–17 August is shown in figure 8. Similar to the first flight, the SDR from the balloon measurements and model calculations was very consistent under both cloudy sky (16 August) and quasi-clear sky (17 August) conditions. The CRF on balloon SUR was 371.5 Wm$^{-2}$ at most at 13:12 when a large cloud amount occurred; the daily mean CRF on balloon SUR was 114.0 Wm$^{-2}$ on 16 August. A close SUR was exhibited by balloon measurements and model calculations under a quasi-clear sky on 17 August. Compared with the model simulations, the surface SDR under a clear sky was not well expressed by the fitting method based on the SDR measurements collected under great cloud cover. A negative CRF dominated the SDR and SUR on August 16, with peaks of −744.4 and −223.6 for SDR and SUR, respectively, at 13:10; their daily average CRFs on the surface SDR and SUR were −191.5 and −59.5 Wm$^{-2}$, respectively, on 16 August, resulting in a net cooling effect of surface shortwave radiation (−132.0 Wm$^{-2}$). The surface measurements and simulations generally agreed on SDR and SUR under quasi-clear sky conditions on 17 August.

The SDR discrepancy between the balloon measurements and surface model simulations under a clear sky should be primarily induced by the synthetic radiative forcing (SRF) of scattering and absorption by atmospheric gases (water vapor, oxygen, ozone, etc.) and aerosols distributed between the surface and balloon flight altitudes. The SRF enlarged rapidly.
during the balloon ascent periods on July 23 and August 16 (figure 9), which is due to the increased radiative effect by increasing gases and aerosols integration as the balloon elevation increased and the solar zenith angle decreased. The diurnal evolution of SRF during the balloon level flight in the UTLS was fairly close on July 23 and August 16. At a more detailed level, the SRF on July 23 was systematically higher than that on August 16, which should be induced by different solar zenith angles and various atmospheric conditions on the 2 d. The peak SRF was approximately ~224 Wm$^{-2}$ at ~16:00; the average of instantaneous SRF was ~194 Wm$^{-2}$ during the periods of the two balloon level flights in the UTLS.

4. Conclusions

Radiation over the TP is vital to climate change but has not been well reported or understood. In this study, the synergy of comprehensive measurements and model simulations is used to understand the radiation characteristics over the TP during the ASM period. The main conclusions are summarized as follows.

Two balloon-borne radiation profiles, which were performed on July 23 and August 16–17 in 2019, exhibited similar variation structures between SDR (SUR) and UVDR (UVUR). The discrepancy between the balloon and surface radiation measurements increased with the ascending periods, which was further enlarged when the cloud formed. The cloud beneath the balloon can reflect SDR and block LUR from the surface, resulting in higher balloon SUR and UVUR and lower LUR than those under a clear sky. The SDR from balloon measurements and model simulations agreed well, with a correlation coefficient, MBE, and RMSE of 0.99, 4.6 Wm$^{-2}$, and 12.6 Wm$^{-2}$, respectively. The daily average AOD440 and ARF were 0.14 and ~41.3 Wm$^{-2}$ on July 23, which was 0.11 and ~31.4 Wm$^{-2}$ on August 17. The average CRFs on the balloon SUR, surface SDR and SUR were 51.3, 7.8 and ~20.1 Wm$^{-2}$, respectively, during the first balloon periods dominated by scattered clouds, leaving a net warming effect of surface shortwave radiation (27.9 Wm$^{-2}$). A much larger CRF on the balloon SUR (114.0 Wm$^{-2}$) was detected on 16 August when cloudy skies prevailed; the CRFs on the surface SDR and SUR were ~191.5 and ~59.5 Wm$^{-2}$, resulting in a net cooling effect of the surface shortwave radiation (~132.0 Wm$^{-2}$). SRF enlarged rapidly during balloon ascent because of the increased radiative effect of gas and aerosol integration and the decreasing solar zenith angle.

The primary objective of this study was to present the radiation properties and CRF over the TP based on two valuable radiation profiles aboard a stratospheric balloon. The aerosol properties and their radiative effects were preliminarily discussed and still require further investigation. One profile of aerosol number density was also measured in the experiment, which detected a well-defined ATAL in the UTLS (Zhang et al. 2020b). As the next step, it is hoped that, by combining more balloon-borne, ground-based and satellite-borne measurements with model simulations, we can better understand the interaction between radiation and clouds over the TP and, more importantly, quantify the ARF of the enhanced ATAL in the UTLS.

Appendix: The descriptions of balloon-borne radiation measurements and the other collocated datasets

A1. The balloon-borne radiation measurements

A radiation profile was provided by six high-quality radiometers that were embedded in an instrument module and attached to the balloon flight platform by a support arm (figure A1(a)). Three radiometers (MS-80, MS-202F and CUF5) are placed upward to the sky to measure downward radiations. The same radiometer configuration is placed downward to the surface to measure upwelling radiation. The spectrum range is 0.285–3, 3–50, and 0.28–0.4 μm for the shortwave, longwave, and ultraviolet radiometers, respectively. The stratospheric balloon, with the maximum radius of 15 m during the flight period, may affect the radiometers measurements by reflecting shortwave radiation and emitting longwave radiation. To reduce this potential influence, the instrument module is hung ~40 m away from the stratospheric balloon. The top (bottom) radiometers are placed 0.3 m above (beneath) the surface of the flight platform; the minimum horizontal distance from the instrument module to the flight platform is 0.3 m.

The flight path of the two stratospheric balloons is shown in figures A1(b) and (c). The first balloon was released at 06:47 on July 23 and ascended to 21 km ASL after approximately 1 h with a mean velocity of ~5 m s$^{-1}$. Then, it flew approximately 21 km until 18:11 when we controlled it to descend. The payload was released by a parachute at 19:25 and landed safely at 19:55. The second balloon was released at 06:42 and ascended to 21 km at ~08:00 on August 16. Then, it flew approximately 21 km until we controlled the balloon to descend to the tropopause (16–17 km) from 23:34 August 16 to 02:17 August 17. The balloon climbed to 21 km again at 04:00. The payload was released by a parachute at 13:00 August 17 when the measurements were terminated. Note that by using the control system designed on the flight platform, we may endeavor to achieve long-term measurements within a limited airspace, as shown by the second launch going through day and night to provide diurnal radiation variations. The balloon flight was away from the QDM spot at most of ~300 km. The instruments were recycled with
Figure A1. Schematic (not to scale) of the radiometer configuration: six radiometers (i.e. two MS-80, two MS-202F, and two CUV5) were embedded in the instrument module (a). The line rising from the surface at the QDM (black rectangle) presents the flight path of the stratospheric balloon on July 23 (b) and 16–17 August (c) in 2019; the color of the line presents the flight time (hours in BJ time), as shown by the color bar above panels (b) and (c); the right color bar shows the ground elevation of the TP (ASL: m).

Figure A2. Level attitude (y-axis: red dots; x-axis: blue dots) of the radiometer measurements on July 23, 2019.

A distance of 1.7 km between landing points of the two flights.

Facilitated by the heavy load (>600 kg in total) aboard the stratospheric balloon, the level attitude of the radiometers was generally stable during the flight in the UTLS (figure A2), although a relatively larger angle of inclination tended to occur during the ascending and descending periods when the quality control and interpolation process was applied to the radiation measurements. We adopted insulation design to the instrument module to ensure that the radiometers are within the required temperature range and thus can work well in the cold atmospheric environment in the UTLS, especially during the nighttime when the temperature can be lower than −70 °C (Zhang et al 2020a).

A2. The other collocated datasets
A Cimel, the standard instrument of the Aerosol Robotic Network (AERONET) (Holben et al 1998),
was deployed to provide solar direct spectral radiation at 10 wavelengths from 340 to 1020 nm and sky radiance at four wavelengths (440, 675, 870, and 1020 nm). The ARF is derived from AERONET Version 2 cloud-screened and quality-assured Level 2 inversion algorithm, which uses the Discrete Ordinate Radiative Transfer module based on the retrieved aerosol size distribution and complex refractive index (Dubovik et al 2006). The radiosonde-based cloud retrieval algorithm of Zhang et al (2010), which was developed based on statistical analyses of temperature and RH measurements, is applied to the radiosonde launches to determine vertical cloud boundaries. More accurate cloud base height is expected than the cloud top height since there is often a delay (time lag) after the radiosonde passes through a cloud layer due to the wetness of the sensors. CALIPSO did not exactly overlap the QDM during the balloon flight periods because of its small footprint. CALIOP measurements within 500 km around the QDM are presented to show spatial distribution and potential transport of aerosols in this study. Aerosols are classified as either tropospheric aerosol or stratospheric aerosol feature types depending on the location of the attenuated backscatter centroid relative to the MERRA-2 reanalysis tropopause height. Aerosols detected above the tropopause are classified as stratospheric aerosols and are assigned subtypes commonly found in the stratosphere. Seven tropospheric aerosol subtypes, i.e. marine, dust, polluted continental/smoke, clean continental, polluted dust (dust and smoke), evaluated smoke (smoke with tops higher than 2.5 km above ground level), and dusty marine (mixtures of dust and marine aerosol) aerosols are determined. Four stratospheric aerosol subtypes, i.e. volcanic ash, sulfate/other, smoke, and polar stratospheric aerosol, are introduced in the product.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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