

# 1 Variability and trend analysis of temperature and height in the upper 2 troposphere and stratosphere region over the tropics (Réunion), by 3 combining balloon-sonde and satellite measurements

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10 **Abstract.** Tropopause height and temperature play a crucial role in atmospheric chemistry and radiative forcing and serve as  
11 key indicators of anthropogenic climate change. However, accurately determining this parameter requires advanced remote  
12 sensing techniques. This study compares tropopause height and temperature estimated from in-situ and remote sensing  
13 instruments (SHADOZ and COSMIC-1) with reanalysis data from MERRA-2 over Réunion from 2006 to 2020. The results  
14 reveal strong agreement between vertical temperature profiles obtained from SHADOZ and COSMIC-1, demonstrating that  
15 both can reliably estimate tropopause height using the Cold Point Temperature (CPT) and/or Lapse Rate Temperature (LRT)  
16 methods. Conversely, while MERRA-2 assimilates data from these sources, its fixed vertical resolution limits its ability to  
17 capture tropopause height variations accurately. Given the consistency between SHADOZ and COSMIC-1, their data were  
18 combined to construct a more refined dataset, which was then used to assess temperature trends. The analysis indicates a high  
19 influence of annual and semi-annual oscillations in Tropopause height dynamics, as well as, a decreasing trend in CPT and a  
20 slight increase in the Lapse Rate Tropopause (LRT) height.

## 21 1 Introduction

22 The troposphere is the atmospheric layer extending from the Earth's surface to around 18 km, depending on the latitude, so it  
23 is generally higher at the equator and decreases toward the poles. Inside this layer can be found the Tropical Tropopause Layer  
24 (TTL), which extends from 12-14 to 18 km, and it represents the transition region between the well-mixed convective  
25 troposphere and the radiatively controlled stratosphere (Fueglistaler et al., 2009; Randel and Jensen, 2013). The TTL is the

26 main gateway for air to enter the stratosphere and a crucial indicator of anthropogenic climate change, as indicated by variations  
27 in the height and/or temperature of the tropopause (Santer et al., 2004).

28 The tropopause, found within the TTL, is a significant physical boundary that separates the unstable and moist troposphere  
29 from the stable and dry stratosphere. The temperature and height of such layer are influenced by both tropospheric and  
30 stratospheric forcing, like as changes in solar radiation (Reid and Gage, 1981), atmospheric angular momentum (Reid and  
31 Gage, 1984), El Niño-Southern Oscillation (ENSO), stratospheric ozone (Hoinka, 1998), Quasi-Biennial Oscillation (QBO)  
32 variability, explosive volcanic eruptions (Reid and Gage, 1985; Randel et al., 2000), and concentrations of Greenhouse Gases  
33 (GHG) (Zou et al., 2023). Consequently, tropospheric warming or stratospheric cooling can result in an increase in the  
34 tropopause height (Santer et al., 2004).

35 Traditional methods for sounding tropopause structure are usually based on in situ measurements (e.g., weather stations,  
36 radiosonde), model data (e.g., reanalysis data) and remote sensing (e.g., lidar, airborne, satellite soundings). The direct  
37 sounding technique usually has an uneven global distribution, with only sparse data distribution, especially in the southern  
38 hemisphere (Santer et al., 2004). On the other hand, reanalyses provide global and temporal coverage and a uniform data type  
39 (Xian and Homeyer, 2019). However, reanalyses suffer from coarser vertical resolution, which can render tropopause height  
40 detection unfeasible (Birner et al. 2006). Considering remote sensing, Global Navigational Satellite System Radio Occultation  
41 (GNSS-RO) stands out for offering accurate tropospheric profiles with high vertical resolution and global coverage  
42 independently of weather conditions. However, they are endowed with lower temporal resolution. Therefore, considering the  
43 limitations and advantages of each methodology, an option to improve the tropopause monitoring is to combine them. Although  
44 firstly it is necessary to identify their similarities and differences.

45 In this context, this study compares vertical temperature profiles from the Southern Additional Ozonesondes (SHADOZ)  
46 network, Constellation Observing System for Meteorology Ionosphere and Climate 1 (COSMIC-1), and Modern Era  
47 Retrospective analysis for Research and Applications – Version 2 (MERRA-2) over Réunion (2006–2020) to identify  
48 similarities and/or differences. Additionally, the study demonstrates how these datasets contribute to understanding variability  
49 in the Upper Troposphere–Lower Stratosphere (UT-LS) region. Finally, by combining ground-based balloon-sonde data and  
50 satellite-based COSMIC-1 observations, the variability and trend estimate of temperature in the tropical UT-LS region were  
51 investigated.

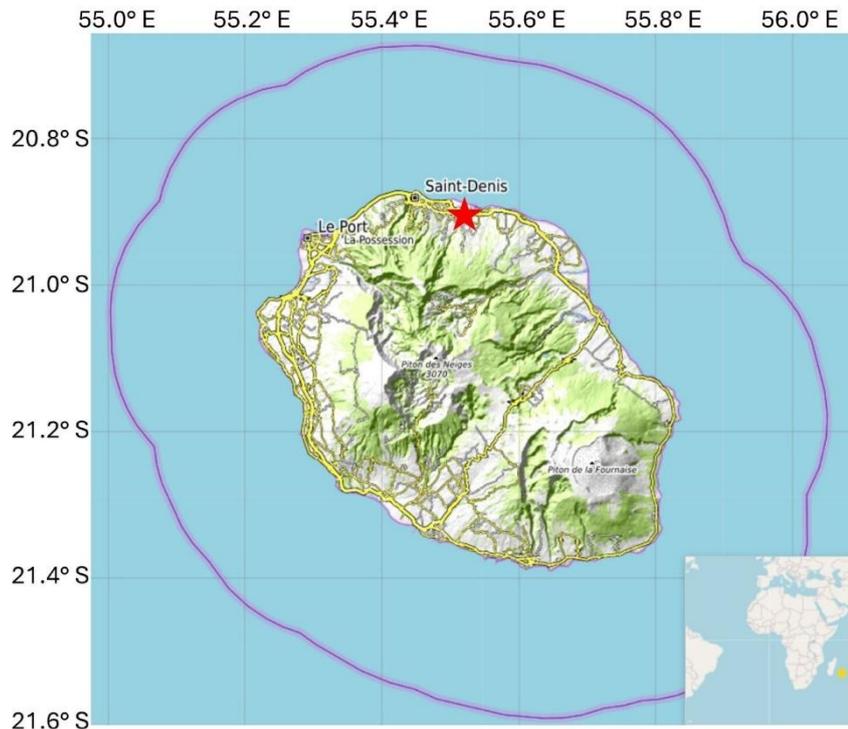
52 The paper structure is as follows: Section 2 gives a brief description of the experimental site and instruments used. The  
53 methodologies applied are presented in section 3. The comparisons between temperatures and tropopause height estimated

54 from SHADOZ, COSMIC-1 and MERRA-2 datasets are presented in section 4. In section 5, the results provided by the Trend-  
55 Run model are described. Finally, the conclusions are given in Section 6.

## 56 2 Materials

### 57 2.1 Study Area

58 Réunion (Fig. 1) is a volcanic island of the Indian Ocean with a population of  $\sim 860,000$  inhabitants. It covers around 2,512  
59 km<sup>2</sup>, and it is characterized by a humid tropical climate tempered by the oceanic influence of the trade winds blowing from the  
60 southeast. In addition, this climate is endowed with great variability, mainly due to the island landscape, which causes  
61 numerous microclimates (Britannica, 2025).



62  
63 **Figure 1: Geographical location of the study site, Réunion, a French overseas department in the southern tropics. The red star**  
64 **symbol indicates the measurement site where the balloon radiosondes are carried out, located to the north of the island at Roland**  
65 **Garros International Airport (20.9° S; 55.5° E).**

### 66 2.2 Measurement by ballon-sonde experiment

67 Radiosonde measurements began in Réunion in 1993 (Baldy et al., 1996), and the station joined the Southern Hemisphere  
68 ADDitional OZonesondes (SHADOZ) network in 1998, increasing the frequency of measurements to weekly. The SHADOZ  
69 network is a NASA project that aims to fill gaps in ozone observation in the southern tropics by increasing radiosonde

70 frequencies at existing stations on a cost-sharing basis (Thompson et al., 2003). Each radiosonde is coupled in a balloon  
71 meteorological sonde, with an electrochemical cell (ECC) ozone-sonde, to transmit in-situ information on air pressure,  
72 temperature, relative humidity, and ozone partial pressure (Witte et al., 2017; Witte et al., 2018). The radiosonde technique  
73 has as its main disadvantages the limited spatial and temporal resolution, which can hinder a detailed observation of the  
74 dynamics of the tropopause. For this study, we used radiosonde temperature profiles from the study site (2006–2020), covering  
75 the COSMIC-1 mission's operational period and overlapping with its measurements. Radiosonde data can be accessed at the  
76 following link on the SHADOZ website (<https://tropo.gsfc.nasa.gov/shadoz/Reunion.html>) (Sterling et al., 2017; Thompson  
77 et al., 2017; Thompson et al., 2021).

### 78 **2.3 Temperature profiles from the COSMIC-1 experiment**

79 The Constellation Observing System for Meteorology, Ionosphere, and Climate 1 (COSMIC-1) is a joint U.S.-Taiwanese  
80 program designed to provide advances in meteorology, ionospheric research, climatology, and space weather by using GNSS-  
81 RO, which is a satellite remote sensing technique that uses GNSS (e.g. Global Positioning System - GPS) measurements  
82 received by low-Earth orbiting satellites to profile the Earth's atmosphere and ionosphere with high vertical resolution and  
83 global coverage (Thompson et al., 2003; Anthes et al., 2008). The COSMIC-1 was launched into a circular low-Earth orbit on  
84 April 15, 2006, and retired in 2020. Its main limitation is the data gap during maintenance periods and after the beginning of  
85 the progressive degradation, which began in 2019 and resulted in total inoperability in May 2020. In this paper, we utilized all  
86 temperature profiles that have been provided by COSMIC-1 between 2006 and 2020. The profiles were selected for a specific  
87 geographic area, covering Réunion with a margin of  $\pm 2^\circ$  in latitude and  $\pm 3^\circ$  in longitude (UCAR COSMIC Program, 2022).

### 88 **2.4 Temperature assimilation from the MERRA-2 reanalysis**

89 The Modern-Era Retrospective Analysis for Research and Applications – Version 2 (MERRA-2) is a global atmospheric  
90 reanalysis produced by the National Aeronautics and Space Administration (NASA) Global Modeling and Assimilation Office  
91 (GMAO). MERRA-2 replaces the original MERRA so that more information is assimilated, such as modern hyperspectral  
92 radiance and microwave observations, along with GPS-Radio Occultation and NASA ozone datasets. Like COSMIC-1 time  
93 cover, we used vertical temperature profiles from MERRA-2 data from 2006 to 2020. Such temperature profiles can be  
94 obtained from the following MERRA-2 product, M2T3NVASM\_5.12.4  
95 ([https://disc.gsfc.nasa.gov/datasets/M2T3NVASM\\_5.12.4/summary](https://disc.gsfc.nasa.gov/datasets/M2T3NVASM_5.12.4/summary)), which is composed of 17 atmospheric variables and has  
96 a spatial resolution of  $0.5^\circ \times 0.625^\circ$ . All data are distributed on 72 pressure levels, ranging from 1000 to 0.01 hPa, with a time  
97 resolution of 3 hours. These fixed heights can make it impossible to adequately observe some variations and trends in the  
98 tropopause behaviour (Zou et al., 2023). In this study, we used MERRA-2 average daily temperature profiles.

### 99 3 Methods

100 This study is based on the combination of 3 sources of temperature profile data at Réunion (radiosonde, COSMIC-1 and  
101 MERRA-2), over 15 years (2006-2020). Such a combination makes it possible to describe the thermal structure of the tropical  
102 atmosphere from the ground up to the mesosphere. However, given the differences in the methods of acquisition and  
103 production, the temperature data used may not offer the same uncertainties, or resolutions everywhere at all altitudes and in  
104 all seasons. The first step is to compare these datasets to each other and define the altitude ranges where they can be used with  
105 confidence. Secondly, one could use all or a combination of these data to construct a coherent and regular time series, to  
106 investigate variability and temperature change in different atmospheric layers. Regarding the values obtained from the methods  
107 described in the following subsections, all reported uncertainties represent  $\pm 2\sigma$  variability unless stated otherwise.

#### 108 3.1 Cold-Point Tropopause

109 Based on thermal properties, it is possible to use the temperature profile to estimate the tropopause height from the Cold-Point  
110 Tropopause ( $TH_{CPT}$ ), which can be defined as the height where the tropospheric temperature reaches its minimum value  
111 (Selkirk, 1993). In this paper, the temperature observed at this height  $z$  is denominated  $T_{CPT}$ . Such definition is given by the  
112 following equation:

$$113 T(z) \begin{cases} T_{CPT} = \min(T(z)) \\ TH_{CPT} = z, \\ \text{where } T(z) = T_{CPT} \end{cases} \quad (1)$$

#### 114 3.2 Lapse-Rate Tropopause

115 From temperature profiles  $T(z)$  it is possible to identify the tropopause height from the lowest level at which the lapse rate is  
116 less than  $2 \text{ K.km}^{-1}$  and it remains within this level for the next 2 km, such a point is denominated as the Lapse-Rate Tropopause  
117 ( $TH_{LRT}$ ) (WMO,1957), which is endowed of high stability, and signifies the thermodynamical transition between the  
118 troposphere and stratosphere. In this paper, the temperature detected at such height is denominated  $T_{LRT}$ . In addition, in all

119 cases of the final time series where the criterium established in the previous paragraph was not identified, the  $TH_{LRT}$  was  
120 classified as NaN.

### 121 3.3 Stratopause Height

122 As defined by France et al. (2012), the stratopause is determined as the altitude where the stratospheric temperature reaches  
123 its maximum in the vicinity of 50 km. Therefore, considering the 3 databases applied in this study, only the COSMIC-1  
124 temperature profiles can be used to detect the stratopause, due to their vertical range and resolution.

### 125 3.4 Forcings parametrization in the Trend-Run model

126 The Trend-Run model, a multiple linear regression model, was first adapted at the University of Réunion to analyse  
127 temperature trends in the southern subtropical upper troposphere-lower stratosphere (UT-LS) (Bencherif et al., 2006). This  
128 model decomposes the variations of a time-series signal,  $S(t)$ , into components representing atmospheric forcings:

$$130 S(t) = c_1SAO(t) + c_2AO(t) + c_3QBO(t) + c_4ENSO(t) + c_5SSN(t) + c_6IOD(t) + \varepsilon \quad (2)$$

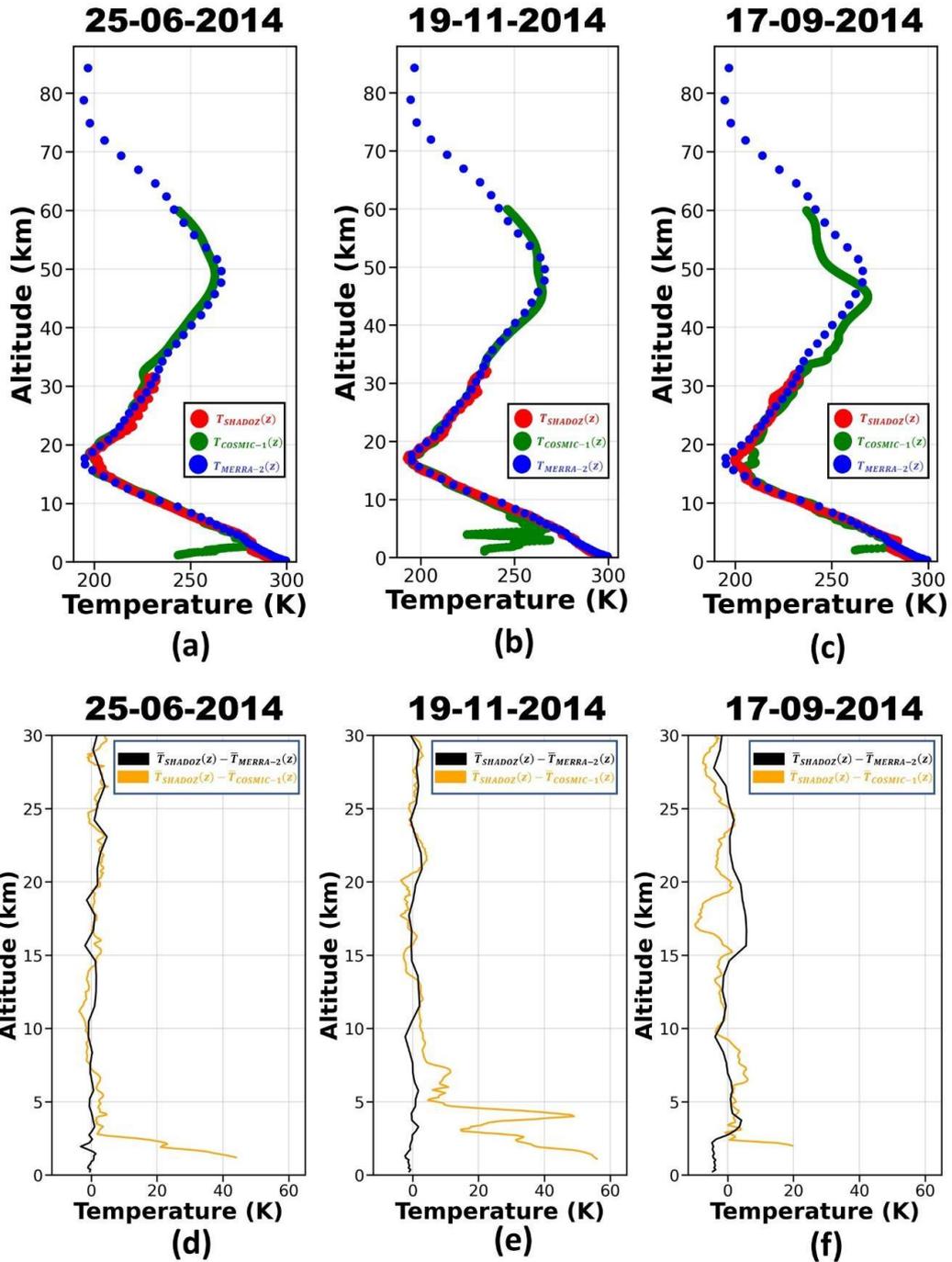
131  
132 where  $\varepsilon$  represents the residuals term which includes the trend, and  $c_i$  (i ranging from 1 to 6) are contribution coefficients of  
133 the respective forcings. The coefficients  $c_i$  can be derived using the least-squares method, which minimizes the residual  
134 variance, while the trend is parameterized as linear:  $Trend(t) = a_0 + a_1t$ , where  $a_0$  is a constant, and  $a_1$  is the trend slope.  
135 The initial model incorporated key forcings, including annual and semi-annual oscillations (AO, SAO), quasi-biennial  
136 oscillation (QBO), El Niño-Southern Oscillation (ENSO), sunspot numbers (SSN), AO and SAO represent seasonal cycles,  
137 with SAO being particularly dominant in the tropics above 35 km altitude. SAO amplitudes decrease with latitude but can  
138 intensify in the subtropics, depending on altitude. QBO is parametrised as a proxy of the zonal wind at 70 hPa derived from  
139 balloon measurements at the Equator (Singapore), while the ENSO is parametrized with the Multivariate ENSO Index (Randel  
140 and Cobb, 1994). The model was further extended by Bègue et al. (2010) to include the Indian Ocean Dipole (IOD), which  
141 describes sea surface temperature (SST) anomalies in the Indian Ocean's east-west dipole (Saji et al., 1999; Morioka et al.,  
142 2010). The IOD, measured by the Dipole Mode Index (DMI), quantifies the SST difference between the western (50°E–70°E,  
143 10°S–10°N) and eastern (90°E–110°E, 10°S–Equator) Indian Ocean (Sivakumar et al., 2017). The DMI data were sourced  
144 from the Japanese Agency for Marine-Earth Science and Technology. The model's performance, measured with the coefficient  
145 of determination ( $R^2$ ), evaluates its ability to explain how much the forcings explain the signal variability. Decadal temperature  
146 trends (in Kelvin) were calculated to evaluate long-term changes. For details on the Trend-Run model and its parameterizations,  
147 see Bencherif et al. (2006) and Bègue et al. (2010).

148 **4 Analysis of temperature profiles**

149 In this section, a comparison is performed among the vertical temperature profiles provided by MERRA-2 ( $T_{MERRA-2}(z)$ ),  
150 SHADOZ ( $T_{SHADOZ}(z)$ ) and COSMIC-1 ( $T_{COSMIC-1}(z)$ ). The limitations and advantages of each system will be presented and  
151 then a database will be created combining the data from the instruments that are endowed of the most similar profiles.

152 **4.1 Day-to-day Comparisons**

153 Figure 2 shows daily comparisons of vertical temperature profiles from SHADOZ ( $T_{SHADOZ}(z)$ ), COSMIC-1 ( $T_{COSMIC-1}(z)$ ),  
154 and MERRA-2 ( $T_{MERRA-2}(z)$ ) for three selected dates: 25 June 2014 (Fig. 2a), 19 November 2014 (Fig. 2b), and 17 September  
155 2014 (Fig. 2c). The corresponding temperature differences (SHADOZ – COSMIC-1 and SHADOZ – MERRA-2) for the same  
156 dates are presented in Figures 2d, 2e, and 2f.



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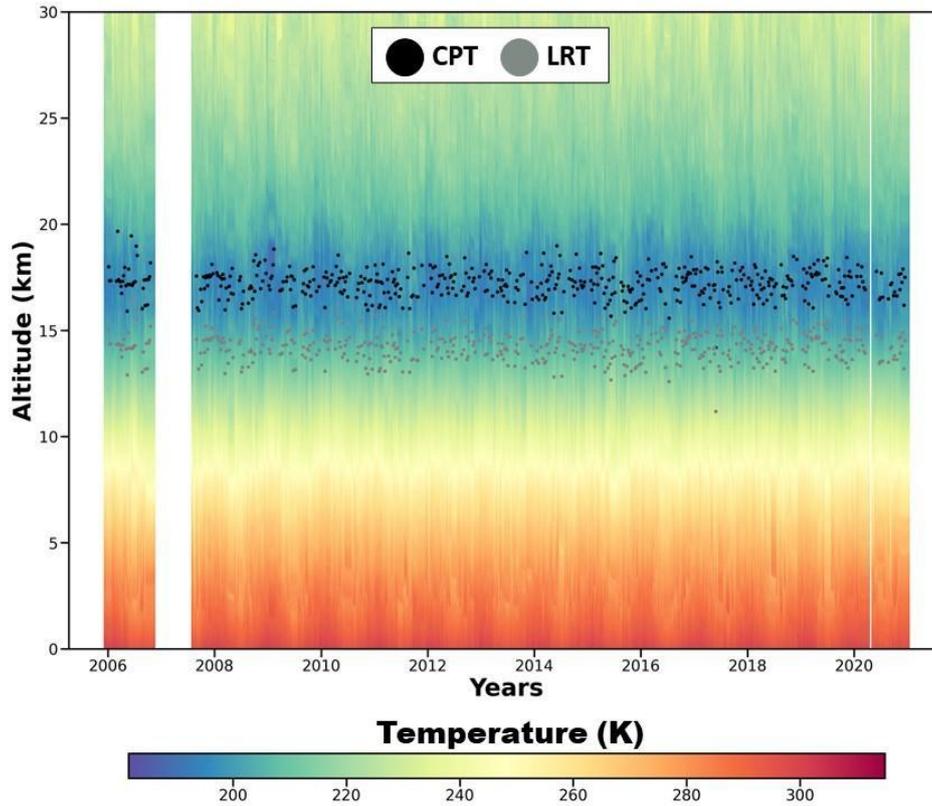
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Figure 2: Comparison between  $T_{SHADOZ}(z)$  (red),  $T_{COSMIC-1}(z)$  (green) and  $T_{MERRA-2}(z)$  (blue) profiles on 25-06-2014 (a), 19-11-2014 (b) and 17-09-2014 (c) and the difference between  $T_{SHADOZ}(z)$  and  $T_{COSMIC-1}(z)$  (orange line) and  $T_{SHADOZ}(z)$  and  $T_{MERRA-2}(z)$  (black line) profiles to the same days (d), (e), and (f), respectively.

161 On 25 June and 19 November, the difference between  $T_{SHADOZ}(z)$  and  $T_{MERRA-2}(z)$  does not exceed 4.0 K, so that the minimal  
162 differences are observed below 6.0 km and in the region between 16.0 km and 18.0 km. On the other hand,  $T_{SHADOZ}(z)$  and  
163  $T_{COSMIC-1}(z)$  present a significant difference below 5.0 km (in some points the difference is higher than 40.0 K). However,  
164 above 10.0 km, on both days,  $T_{SHADOZ}(z)$  and  $T_{COSMIC-1}(z)$  are very similar, so that the difference does not exceed 5.0 K.  
165 On 17 September,  $T_{SHADOZ}(z)$  and  $T_{MERRA-2}(z)$  present a difference lower than 5.0 K in the region below 15.0 km. Above  
166 15.0 km, the difference increases significantly, mainly in the region between 15.0 and 20.0 km. As observed in the other two  
167 days, the higher difference between  $T_{SHADOZ}(z)$  and  $T_{COSMIC-1}(z)$  is observed in the first 5.0 km. However, a significant  
168 difference (around 6 K) also is observed in the region between 15.0 and 20.0 km, resulting in a variation of approximately 2.1  
169 km between the CPT estimated by  $T_{SHADOZ}(z)$  (17.3 km) and  $T_{COSMIC-1}(z)$  (15.2 km). In addition, a difference between  
170  $T_{COSMIC-1}(z)$  and  $T_{MERRA-2}(z)$  in the region above 30.0 km is significantly higher than that observed in previous analyses.  
171 However, as will be demonstrated in the next sections, it is possible to consider 17 September as an exceptional case, where  
172  $T_{COSMIC-1}(z)$  presents an abnormal behavior.

#### 173 **4.2 Weekly (SHADOZ) and daily (COSMIC-1) temperature profiles**

174 Figure 3 presents the curtain plot from the ground up to 30.0 km of weekly temperature profiles as measured by balloon-sondes  
175 ( $T_{SHADOZ}$ ) at Réunion from 2006 to 2020. The figure shows that during this period, balloon-sonde measurements at Réunion  
176 were carried out almost continuously, at the rate of one release per week, except in 2007, due to a shortage of stock supplies,  
177 which resulted in a 3-month interruption. For each profile, the tropopause height was determined and corresponds to the  
178 location of the LRT ( $LRT_{SHADOZ}$ ) and CPT ( $CPT_{SHADOZ}$ ), as defined above. Their respective positions are superimposed in  
179 Figure 3 by grey and black dots. Overall, the altitude of the  $CPT_{SHADOZ}$  varies between 16.0 and 19.0 km, with an average  
180 position of  $[17.2 \pm 1.4]$  km, while the  $LRT_{SHADOZ}$  varies between 14.0 and 16.0 km, with an average value of  $[14.9 \pm 1.5]$  km,  
181 resulting in an average difference of  $[2.3 \pm 0.3]$  between  $CPT_{SHADOZ}$  and  $LRT_{SHADOZ}$ . The range of  $CPT_{SHADOZ}$  values agrees  
182 with the results reported by Bègue et al. (2010), and with the average value obtained by Sivakumar et al. (2006)  $[17.2 \pm (1\sigma)$   
183  $0.6]$  km. On the other hand, the  $LRT_{SHADOZ}$  range is below of Bègue et al. (2010) results, as well as the average value is lower  
184 than that one reported by Sivakumar et al. (2006)  $[16.0 \pm (1\sigma) 0.7]$  km. Consequently, the average difference between  
185  $CPT_{SHADOZ}$  and  $LRT_{SHADOZ}$  is higher than the values obtained by Bègue et al. (2010), Sivakumar et al. (2006), and Zhran et al.  
186 (2023)  $[0.91 \pm (1\sigma) 0.15]$  km,  $[1.09 \pm (1\sigma) 0.94]$  km, and 0.92 km, respectively. It is important to highlight that the number of  
187  $LRT_{SHADOZ}$  cases are lower than those of  $CPT_{SHADOZ}$ , as not all  $T_{SHADOZ}(z)$  profiles have the essential characteristics for  
188 calculating the LRT.



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**Figure 3: Time-height temperature cross-section over Réunion from weekly balloon-sonde profiles from January 2006 to December 2020. Black and gray dots indicate the CPT and LRT heights, respectively.**

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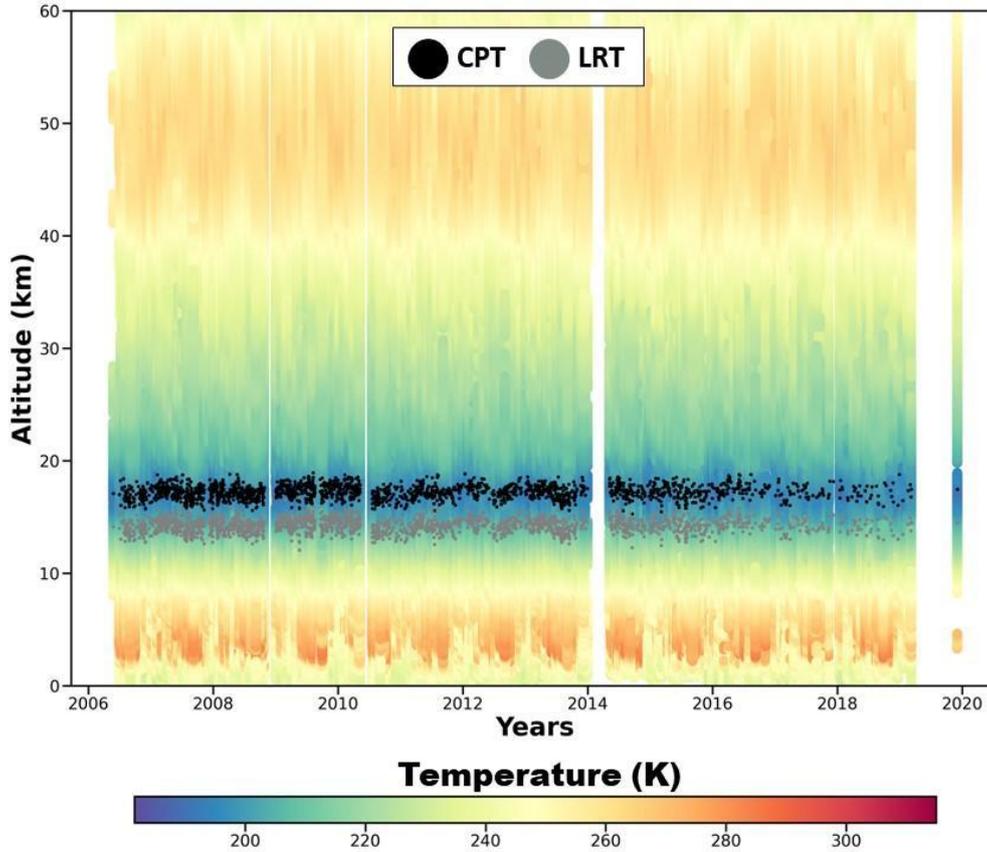
Similar to Figure 3, Figure 4 presents the curtain plot of the vertical temperature profiles from the surface to 60.0 km height, as derived from daily COSMIC-1 measurements from 2006 to 2020. By comparison to SHADOZ temperature profiles, COSMIC-1 profiles present a higher vertical range, up to the mesosphere (limited here to 60.0 km) with greater temporal sampling. Table 1 presents the total number of temperature profiles per month used in the present study from SHADOZ and COSMIC-1 measurements. COSMIC-1 presents a lack of data in February and March 2014, and from June to December 2019. In addition, based on the density of CPT and LRT points in Figure 4, it can be noted that there was a decrease in the number of COSMIC-1 overpasses over the study site from 2017.

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A quick visual comparison of the  $T_{SHADOZ}$  (Figure 3) and the  $T_{COSMIC-1}$  (Figure 4) shows significant differences below 10 km altitude. The CPT values obtained from COSMIC-1 data ( $CPT_{COSMIC-1}$ ) are located in the same range of  $CPT_{SHADOZ}$ , so that the average value provided by COSMIC-1 data [ $17.2 \pm 1.3$ ] km is similar to average  $CPT_{SHADOZ}$  [ $17.2 \pm 1.4$ ] km and almost identical to the value obtained by Sivakumar et al. (2006). Regarding the LRT ( $LRT_{COSMIC-1}$ , the range of values [between 14.0 and 16.0 km] and the average value [ $14.7 \pm 1.2$ ] km) are similar to that one obtained from SHADOZ data, consequently the average difference between  $CPT_{COSMIC-1}$  and  $LRT_{COSMIC-1}$  [ $2.9 \pm 1.9$ ] km is similar to that one observed between the

204

205 SHADOZ data. These results agree with those presented by Xia et al (2021), who found an average difference of 2.67 km  
 206 between  $CPT_{COSMIC-1}$  and  $LRT_{COSMIC-1}$ .

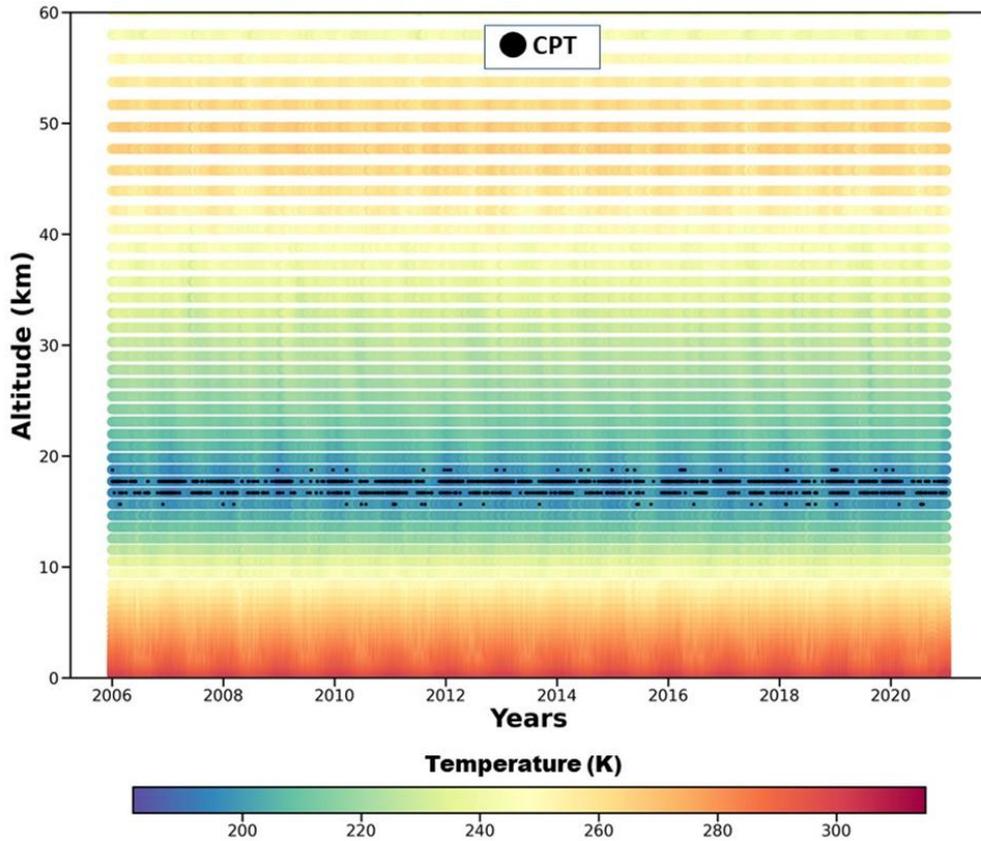


207  
 208 **Figure 4: Same as Figure 3 but concerning COSMIC-1 measurements over Réunion.**

209  
 210 **Table 1: Total monthly number of temperature profiles used from SHADOZ and COSMIC-1 measurements at the Réunion site.**

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total
SHADOZ	40	43	46	46	45	53	30	24	54	48	43	32	504
COSMIC-1	159	163	197	175	158	169	223	216	162	164	112	99	1997

211  
 212 In contrast to SHADOZ and COSMIC-1 data, MERRA-2 does not show any data gap (Fig. 5). Although the  $T_{MERRA-2}$  have a  
 213 reasonable agreement with  $T_{SHADOZ}$  and  $T_{COSMIC-1}$  in tropopause region (Fig. 2), MERRA-2 data cannot be used to detect the  
 214 tropopause height accurately, because the heights are fixed, as mentioned previously, then the results obtained have low  
 215 variability, making it impossible to observe the variations and trends in this layer (Fig. 5). Zou et al. (2023), when comparing  
 216 CPT and LRT values using different reanalysis databases (ERA-Interim, MERRA-2 and NCEP/NCAR Reanalysis 1), also  
 217 address the difficulty of refinement due to the coarser vertical resolution.



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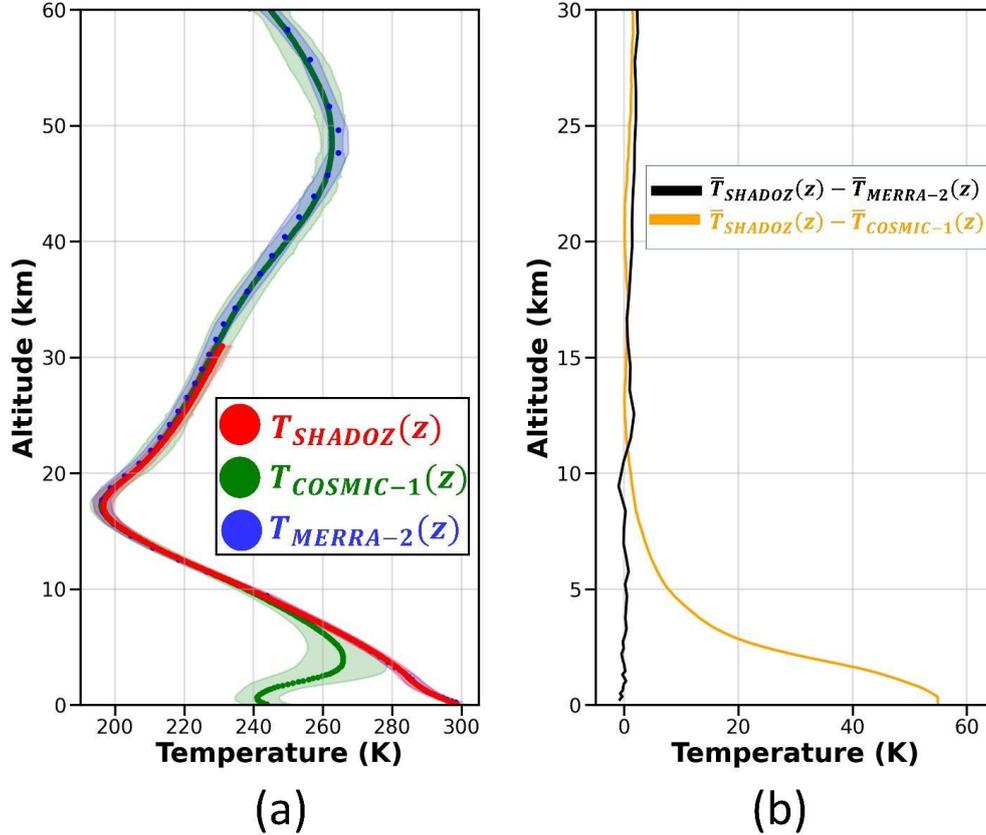
219 **Figure 5: Time-height temperature cross-section over Réunion from daily MERRA-2 data from January 2006 to December 2020.**  
 220 **The black dots indicate the CPT.**

### 221 4.3 Global Comparison

222 In this subsection, the global mean temperature profiles obtained from the 3 datasets (SHADOZ, COSMIC-1 and MERRA-2)  
 223 were computed and compared with each other. A global temperature profile is obtained by averaging all the temperature  
 224 profiles recorded by the same experiment over the entire study period (2006-2020). We thus obtained 3 global average profiles  
 225 for the 3 datasets:  $\bar{T}_{SHADOZ}(z)$ ,  $\bar{T}_{COSMIC-1}(z)$ , and  $\bar{T}_{MERRA-2}(z)$ . They are superimposed in Figure 6(a), respectively in red,  
 226 green and blue dots. Figure 6(b) shows the temperature differences in the 0.0 - 30.0 km altitude range between the COSMIC-1  
 227 and MERRA-2 global profiles and the SHADOZ global profile:  $(\bar{T}_{SHADOZ}(z) - \bar{T}_{COSMIC-1}(z))$  and  $(\bar{T}_{SHADOZ}(z) -$   
 228  $\bar{T}_{MERRA-2}(z))$ , respectively in orange and black lines. Using SHADOZ data as a reference, it is evident that COSMIC-1  
 229 temperature values progressively overestimate as height decreases below 8.0 km, whereas MERRA-2 assimilated temperatures  
 230 show excellent agreement. The largest differences are obtained between SHADOZ and COSMIC-1 values in the lower  
 231 troposphere, up to 55.0 K near the surface (see Figure 6b).

232 Above 10.0 km, the differences between  $\bar{T}_{COSMIC-1}$  and  $\bar{T}_{SHADOZ}$  reach approximately 1.0 K, continuing in this way until the  
 233 end of the  $\bar{T}_{SHADOZ}$  profile (around 30.0 km).  $\bar{T}_{MERRA-2}$  appears as a combination between  $\bar{T}_{SHADOZ}$  and  $\bar{T}_{COSMIC-1}$ , following

234 the behavior of SHADOZ in the first 30.0 km, so that the average profiles do not present a difference greater than 2.0 K, and  
 235 follows COSMIC-1 in the rest of the profile. Such behavior was also observed by Tegmeier et al. (2020). The similarity of  
 236  $T_{MERRA-2}$  with  $T_{SHADOZ}$  and  $T_{COSMIC-1}$  is justified by the composition of the MERRA-2 reanalysis data, since in addition to  
 237 being based on balloon-sonde profiles, these reanalysis data incorporate GPS-Radio Occultation information, which did not  
 238 happen with the original MERRA data.



239  
 240 **Figure 6:** (a) Global average temperature profiles over Réunion site from SHADOZ (red line), COSMIC-1 (green line) and MERRA-  
 241 2 (blue line), framed with their  $\pm 2\sigma$  (standard deviation) profiles (in coloured shadows). (b) Difference profiles:  
 242  $(\bar{T}_{SHADOZ} - \bar{T}_{MERRA-2})$  and  $(\bar{T}_{SHADOZ} - \bar{T}_{COSMIC-1})$ , respectively in black and orange lines.

243

#### 244 4. 4 Seasonal Comparison

245 As reported by several authors (Seidel et al., 2001; Bencherif et al., 2006; Sivakumar et al., 2011a; Bègue et al., 2010;  
 246 Shangguan and Wang, 2022; Zhran and Mousa., 2023), the thermal structure of the atmosphere is seasonally dependent,  
 247 notably in the tropics and subtropics. Thus, we examined and compared temperature profiles averaged by season (summer -  
 248 DJF, autumn -MAM, winter -JJA and spring -SON). Plots in the upper panel of Figure 7(a—d) superimpose the seasonal

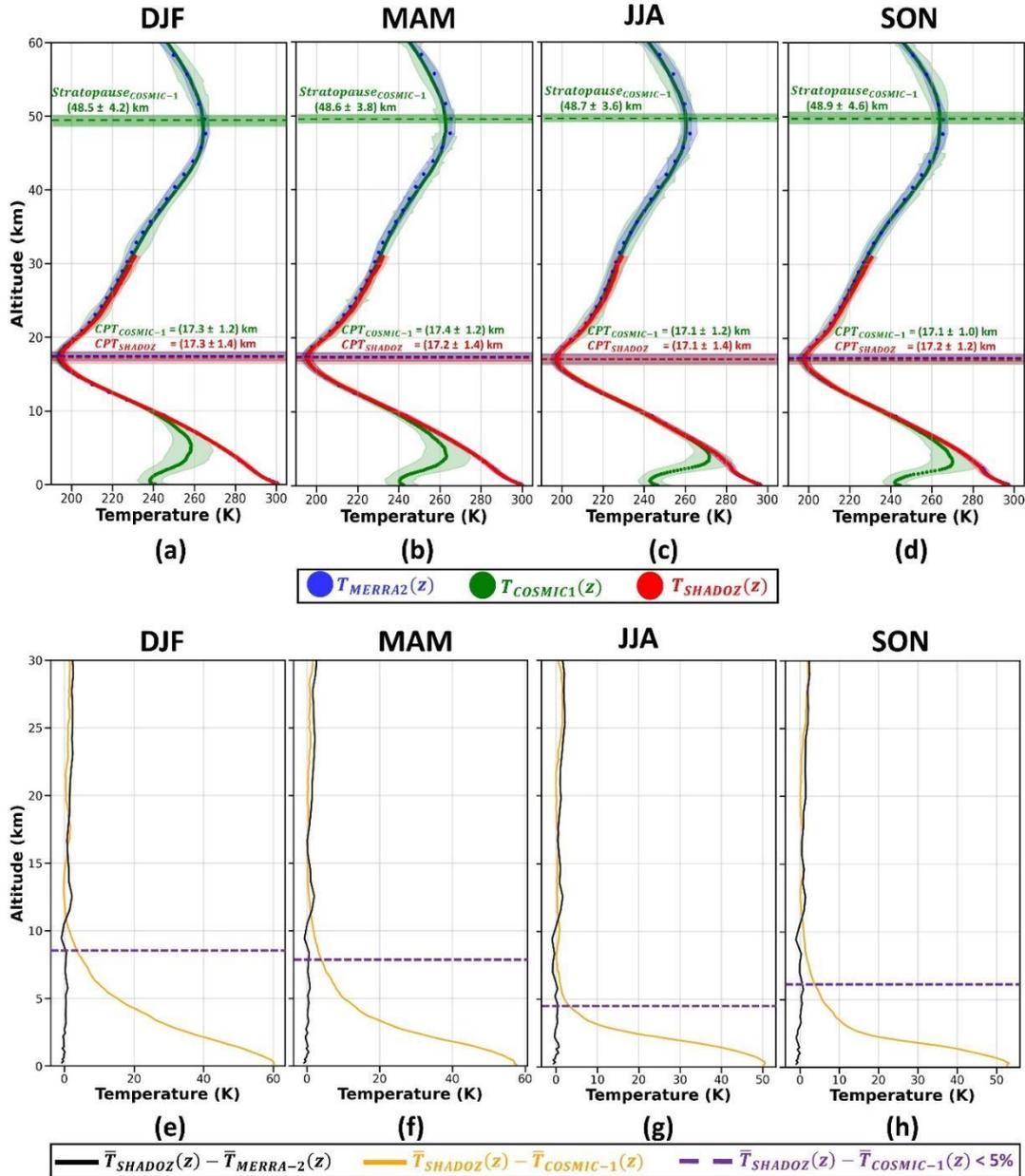
249 temperature profiles obtained from SHADOZ, COSMIC-1 and MERRA-2 and the associated seasonal temperature differences  
250 with the SHADOZ data as a reference (plots of the lower panel of Fig. 7e - h).

251 The altitude range of agreement between the seasonal  $\bar{T}_{SHADOZ}$  and  $\bar{T}_{COSMIC-1}$  temperature profiles vary depending on the  
252 season, as indicated in Figure 7(b). To enable comparison between different seasons, a horizontal dashed line is added to the  
253 temperature difference profiles. This line shows the altitude at which the temperature difference between  $\bar{T}_{SHADOZ}$  and  
254  $\bar{T}_{COSMIC-1}$  begins to be lower than 5%. It appears from this line that the altitude of validity of the COSMIC-1 measurements  
255 depends on the season. It is possible to identify a seasonal behavior, where the highest limit occurs in summer (5.3 km), then  
256 it decreases continuously, reaching 4.3 km in Autumn, and the lowest value in winter and spring (2.8 km). The best agreement  
257 between  $\bar{T}_{SHADOZ}$  and  $\bar{T}_{COSMIC-1}$  values are observed during the dry season (JJA), while during the wet season (DJF)  $\bar{T}_{COSMIC-1}$   
258 profiles seem to underestimate the  $\bar{T}_{SHADOZ}$  values over the widest range of altitudes. On the other hand, the difference between  
259  $\bar{T}_{SHADOZ}$  and  $\bar{T}_{MERRA-2}$  does not present a seasonality. During all seasons, the differences do not exceed 3.0 K. The higher  
260 values are observed between 11.0 and 14.0 km, and above 19.0 km. In these regions difference between  $\bar{T}_{SHADOZ}$  and  $\bar{T}_{MERRA-2}$   
261 is higher than that one observed between  $\bar{T}_{SHADOZ}$  and  $\bar{T}_{COSMIC-1}$ .

262 The CPT values estimated by both databases are quite similar, so that when considering the uncertainty values, it can be stated  
263 that the seasonal values obtained from COSMIC-1 and SHADOZ are practically coincident. The  $CPT_{COSMIC-1}$  sometimes  
264 overestimates and at others underestimates the  $CPT_{SHADOZ}$ . The lower absolute difference between them is observed during  
265 the Winter (26 m), and the higher one in Autumn (122 m). The average  $CPT_{SHADOZ}$  has a seasonal behavior similar to that one  
266 observed by Seidel et al. (2001), where the maximum and minimum values were observed in Summer and Winter, respectively.  
267 Bègue et al. (2010) also identified the maximum  $CPT_{SHADOZ}$  during the summer, as well as Astudillo et al. (2020) using  
268 Ground-Based GNSS Observations and Schmidt et al. (2004) using GPS RO data from the German CHAMP (CHALLENGING  
269 Minisatellite Payload) satellite mission. This seasonal tropopause behavior also was observed by Sivakumar et al. (2011a),  
270 which identified the minimum  $CPT_{SHADOZ}$  during the winter, and Zhran and Mousa (2023). On the other hand, although the  
271 lowest values of  $CPT_{COSMIC-1}$  occur during winter, in agreement with the results obtained by Seidel et al. (2001) and Sivakumar  
272 et al. (2011a), the maximum values occur in autumn, what is not in agreement with the current literature. It is important to  
273 highlight that this seasonal behaviour reinforces the influence of solar radiation in tropopause height, mainly in tropical and  
274 subtropical regions (Sivakumar et al., 2011a).

275 Regarding the  $CPT_{SHADOZ}$  temperature, the average monthly values obtained are similar, although a little bit smaller than those  
276 estimated by Bègue et al. (2010), so that the lower and higher mean absolute difference are -0.1 K (February, the coldest month  
277 identified by Bègue et al. (2010)) and -1.5 K (September, the hottest month identified by Bègue et al. (2010)), respectively. In  
278 this work the coldest month is January ( $[193.1 \pm 4.6]$  K) and the hottest is October ( $[197.1 \pm 4.6]$  K). Considering  $CPT_{COSMIC-1}$ ,  
279 excepting May, where the average  $CPT_{COSMIC-1}$  is 2.7 K higher than the  $CPT_{SHADOZ}$  obtained by Bègue et al. (2010), all other  
280 months have a smaller average temperature value, so that the lower and higher absolute difference are -0.3 (August) and -2.7

281 (April), respectively. The coldest and the hottest month are February ( $[192.1 \pm 4.6]$  K) and September ( $[197.5 \pm 4.8]$  K), as  
 282 observed by Bègue et al. (2010), respectively.



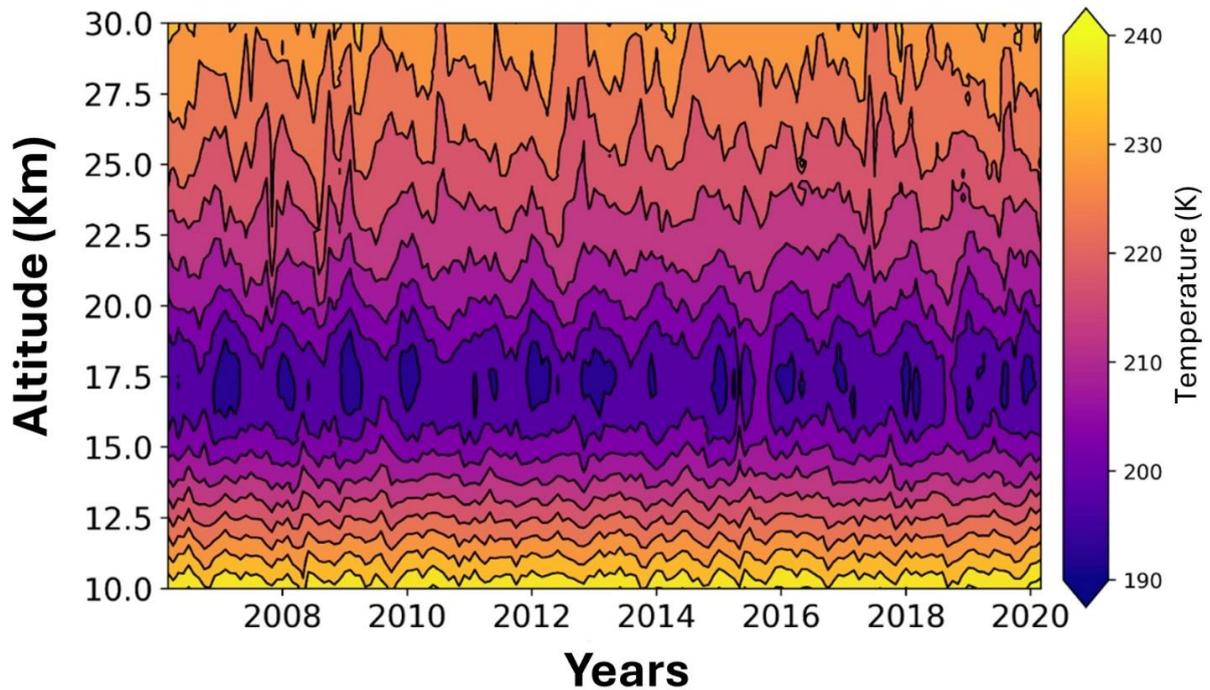
283  
 284 **Figure 7: In the upper part is presented a seasonal comparison ((a) DJF, (b) MAM, (c) JJA, and (d) SON) among  $T_{SHADOZ}(z)$  (red),**  
 285  **$T_{COSMIC-1}(z)$  (green) and  $T_{MERRA-2}(z)$  (blue) profiles, and their respective standard-deviations. In the lower part is presented a**  
 286 **seasonal comparison ((e) DJF, (f) MAM, (g) JJA, and (h) SON) among the differences of  $T_{SHADOZ}(z)$  and  $T_{MERRA-2}(z)$  (black line)**  
 287 **and  $T_{SHADOZ}(z)$  and  $T_{COSMIC-1}(z)$  (orange line). The dotted purple line represents the height where the difference between**  
 288  **$T_{SHADOZ}(z)$  and  $T_{MERRA-2}(z)$  is lower than 5%.**

289

290 Due to the necessity of data above 40 km, only  $T_{COSMIC-1}$  was applied to estimate the stratopause height, as indicated previously  
291 in section 3.3. The stratopause appears to be highest in spring ( $[48.9 \pm 4.6]$  km) with a maximum temperature of  $[266.3 \pm 0.4]$   
292 K, whereas it is lowest in summer ( $[48.5 \pm 4.2]$  km) with a temperature maximum of around  $[267.2 \pm 0.8]$  K. These results  
293 agree with the outcomes of other studies conducted at tropical locations. Batista et al. (2009) analyzed 14 years (from 1993 to  
294 2006) of temperature profiles recorded by a sodium resonance LiDAR at São José dos Campos, Brazil (23°S, 46°W). They  
295 found that the local stratopause altitude was  $\sim 49$ km, with the maximum temperature varying from 265 to 270K. Moreover,  
296 Sivakumar et al. (2011b) used temperature profiles over Réunion recorded between 1994 and 2007 by a Rayleigh LiDAR and  
297 reported that the stratopause height occurrence was in the 47–49 km height range, with temperatures ranging from 260 K to  
298 270 K. In addition, the same seasonal behaviour of the stratopause height presented in Figure 6 was observed by France et al.  
299 (2012) and Vignon and Mitchell (2015) in their climatology studies using the Microwave Limb Sounder (MLS) and reanalysis  
300 data (MERRA-2).

#### 301 **4. 5 Combination between SHADOZ and COSMIC-1 datasets**

302 Considering the results presented in the previous section, where SHADOZ and COSMIC-1 temperature profiles showed a  
303 good agreement in the 10-28 km altitude range, we merged the two datasets to construct quasi-continuous and regular space-  
304 by-time matrix temperature values. SHADOZ and COSMIC-1 have different temporal resolutions (1 profile per week and 1  
305 profile every 2 days, respectively), as mentioned in Section 4.2. Therefore, the final database was created from the combination  
306 of these two datasets, and for days where there is data from both instruments, only the SHADOZ data were considered. Then,  
307 the daily temperature series obtained were reduced to monthly and kilometric averages and are presented in Figure 8. This new  
308 dataset will be applied in the trend analyses (section 5).



309

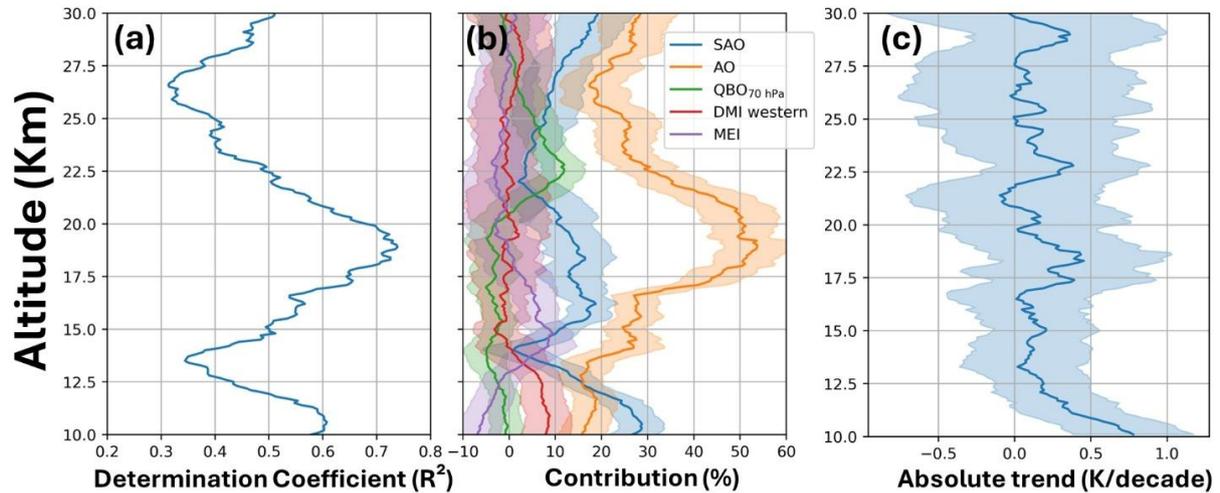
310 **Figure 8: Monthly time-height temperature cross-section over Réunion constructed by combining SHADOZ and COSMIC-1**  
 311 **profiles.**

### 312 **5 Trend Model Analysis**

313 For trend analysis, we used the multiple linear regression method taking into account the same *forcings* used by Bègue et al.  
 314 (2010) and by Tohir et al. (2018): annual and semi-annual cycles, quasi-biennial oscillation, and ENSO (section 3.4).

315 The analysis of the  $R^2$  profile, as depicted in Fig.8a, reveals two layers where the Trend-Run model performs well and explains  
 316 more than 65% of the temperature variability: one layer at around 10 km and another at around 18 km. Additionally, the  $R^2$   
 317 profile shows two minima ( $\sim 40\%$ ), where the Trend-Run model performs less well, in the upper troposphere (14 km) and the  
 318 upper stratosphere (26–27 km). This result is not surprising given the short length of the time series (2006–2020). We then  
 319 examine temperature trends in two tropospheric heights (10 km and 15 km) and two stratospheric layers (19 km and 24 km),  
 320 in addition to temperature trends at the local tropopause. Figure 8b overlays the profiles of the considered *forcings* as derived  
 321 from the Trend-Run model. Overall, the annual oscillation (AO) emerges as the most dominant forcing, particularly in the  
 322 lower stratosphere, where it accounts for over 40% of the variability at approximately 19 km. The semi-annual oscillation  
 323 (SAO) exhibits its maximum contribution in the troposphere, specifically at 10–11 km. The ENSO forcing displays an absolute  
 324 maximum contribution of -20 % in the lower stratosphere (22–23 km) and has a nearly constant contribution of approximately

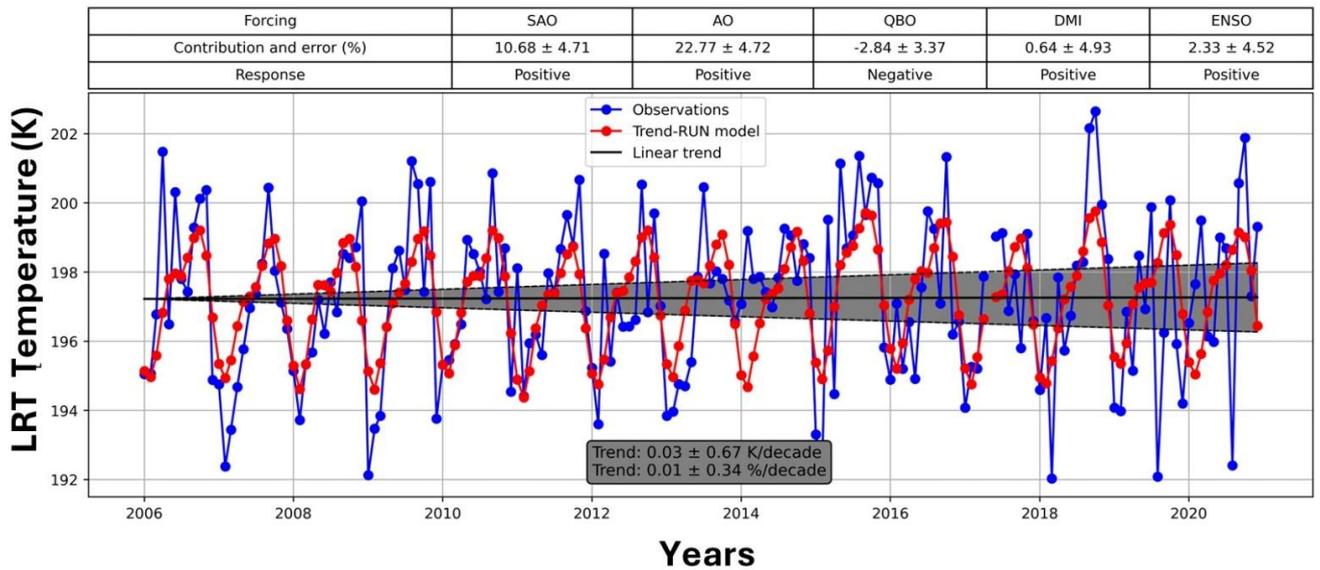
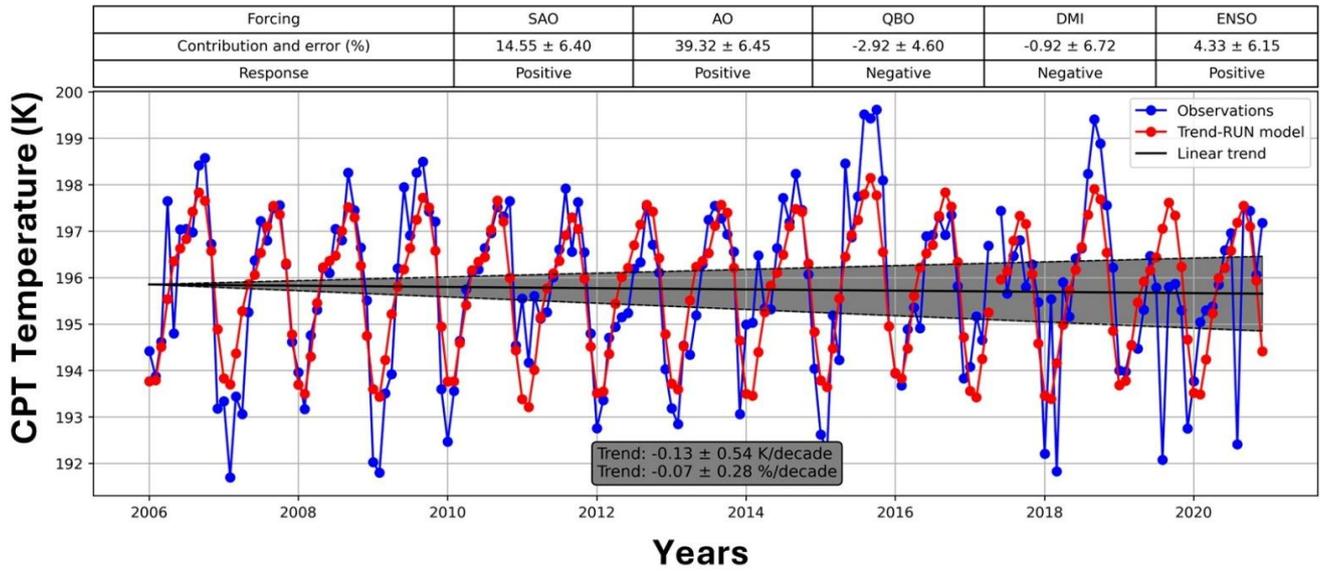
325 10% in the troposphere. The QBO index, obtained for the 70-hPa pressure level, shows almost no contribution in the  
 326 troposphere and a quasi-constant contribution in the stratosphere (~4%).  
 327 Following Figure 9(a), the higher determination coefficient can be observed in the UTLS region (18 – 20 km), so the higher  
 328 contribution, in this region, in the trend model is from AO (Fig. 9b). In addition, such a region presents an increase of around  
 329 0.25 K/decade (Fig. 8c).  
 330



331  
 332 **Figure 9: (a) autocorrelation coefficient profile, (b) vertical profile of contribution of each forcing, (c) vertical profile of absolute**  
 333 **variation of temperature per decade.**

334 Figure 10 shows temperature trends at the tropopause, CPT (Fig.10a) and LRT (Fig.10b) as well as, their standard deviations  
 335 at the  $2\sigma$  level (dotted line). So that the standard deviation associated with the trend value corresponds to uncertainty in the  
 336 trend slope. Temperature at the CPT presents a decreasing trend of  $[-0.13 \pm 0.27]$  K/decade, where seasonal cycles (AO, SAO)  
 337 seem to be the most dominant forcing Zou et al. (2023), using ERA5 data, observed a tropopause cooling of  $[-0.09 \pm 0.03]$   
 338 K/decade from 1980 to 2021. Although the time interval (1979-2005) is different from the present study, Tegtmeier et al.  
 339 (2020) reported a cooling of the tropical CPT from -0.3 to -0.6 K/decade.

340  
 341  
 342



343

344 **Figure 10: Trend model of CPT (a) and LRT (b) temperature variation. The black lines represent the trend of CPT and LRT**  
 345 **temperature, in figures a and b, respectively. The dotted black lines, in both figures, represent the standard deviation of the**  
 346 **temperature trend at the  $2\sigma$  level.**

347

348 On the other hand, LRT temperature (Fig. 10) shows a little insignificant increase ( $[0.03 \pm 0.33]$  K/decade), where in the same  
 349 way as CPT temperature, the seasonal cycles (AO, SAO) are the most dominant forcing. Shangguan and Wang (2022) and  
 350 Negash and Raju (2024) also observed a strong influence of AO and SAO in the UT-LS region from COSMIC-1 and ERA-5

351 data, and COSMIC-1 and Radiosonde data respectively in subtropical latitudes. Following Frierson (2006), the latent heat  
352 release caused by thermal forcing in the troposphere is what creates the strong AO in temperature. In addition, according to  
353 Loon and Jenne (1969), tropical and sub-tropical SAO are most pronounced in the areas where the Intertropical Convergence  
354 Zone crosses the Equator twice a year, in particular, from Eastern Africa to the central Pacific Ocean, which coincides with  
355 the region where Réunion is located.

356 Furthermore, it is important to highlight that the observed trends for both the CPT (cooling) and the LRT (warming)  
357 temperatures are directly associated with tropospheric warming, which has been exacerbated by intense accumulation of GHG  
358 in the lower troposphere as described by Ladstädter et al., 2023. This phenomenon is a key indicator of climate change and  
359 has been observed globally (Ladstädter et al., 2025), reinforcing the intense effect of anthropogenic activities across the planet.

## 360 **6 Conclusions**

361 Tropopause temperature and height serve as key indicators of anthropogenic climate change, influenced by factors such as  
362 stratospheric ozone, greenhouse gas concentrations, and volcanic activity. However, monitoring their variability remains  
363 challenging due to the sparse distribution of observation stations, particularly in the Southern Hemisphere. To address this, we  
364 compared temperature profiles from three datasets—SHADOZ, COSMIC-1, and MERRA-2—to assess their similarities and  
365 differences and to develop a refined dataset for trend analysis. Our analysis of SHADOZ and COSMIC-1 data (2006–2020)  
366 revealed strong agreement in temperature profiles above 10 km. MERRA-2 data showed a good correlation with SHADOZ up  
367 to 30 km and with COSMIC-1 above 30 km, but its coarse vertical resolution limited its applicability for tropopause height  
368 estimation. Using the Cold Point Tropopause (CPT) and Lapse Rate Tropopause (LRT) methods, we found that CPT-derived  
369 tropopause heights and temperatures were consistent across SHADOZ and COSMIC-1, whereas LRT values varied more due  
370 to differences in vertical resolution. Comparisons within each dataset confirmed that LRT-derived tropopause heights were  
371 systematically lower than those from CPT, while LRT temperatures were higher—consistent with previous studies.  
372 Additionally, CPT exhibited seasonal variability, with higher values in summer and lower values in winter. To enhance data  
373 coverage, we created a new dataset by integrating COSMIC-1 data into SHADOZ profiles between 10 and 30 km, preserving  
374 the seasonal characteristics observed in both datasets. This combined dataset improves the representation of tropopause  
375 dynamics in regions with sparse observations. Trend analysis highlighted the significant influence of the annual oscillation  
376 (AO), particularly in the upper troposphere–lower stratosphere (UT-LS) region. We observed a decreasing trend in CPT  
377 temperature ( $-0.13 \pm 0.27$  K/decade) and a slightly increasing trend in LRT temperature ( $0.03 \pm 0.33$  K/decade), both  
378 predominantly influenced by AO and the semi-annual oscillation (SAO). Our findings demonstrate the value of COSMIC-1  
379 data in studying tropopause dynamics, enabling the extension of time series in regions with radiosonde observations and  
380 providing critical data where in situ measurements are unavailable. This study underscores the potential of satellite-based  
381 remote sensing to enhance our understanding of climate-related changes in the tropopause.

382 *Code and data availability.* All observational data analysed in this work are third-party archives and are not generated by the authors: (i)  
383 COSMIC-1 data available from UCAR webpage (<https://www.cosmic.ucar.edu/what-we-do/cosmic-1/data>); (ii) SHADOZ data available  
384 from NASA Goddard Space Flight Center Website (<https://doi.org/10.57721/SHADOZ-V06> and <https://doi.org/10.57721/SHADOZ-V01-UNC>); (iii) MERRA-2 data available from NASA GMAO Website (<https://gmao.gsfc.nasa.gov/gmao-products/merra-2/>). All analyses were  
385 performed using open-source Python libraries.  
386

387 *Author contributions.* G.A. Moreira and H. Bencherif: Conceptualization, Methodology, Software, Analysis, Investigation, Data curation,  
388 Visualization, Writing—original draft, Writing and Editing, Funding acquisition, Data Resources and, Supervision. T. Millet:  
389 Conceptualization, Methodology, Software, Analysis, Investigation, Data curation, Visualization, Writing—original draft, Writing and  
390 Editing. D. K. Pinheiro: Conceptualization, Supervision, Analysis, Writing—original draft, Investigation, Writing and Editing, All authors  
391 approved the final manuscript.

392 *Competing interests.* The contact author has declared that none of the authors has any competing interests.

393 *Acknowledgements.* We acknowledge UCAR, NASA (Goddard Space Flight Center and GMAO). The authors also acknowledge the  
394 following Brazilian Agencies: the National Nuclear Energy Commission (CNEN) (Project: 01342.006470/2023-73) and the Coordination  
395 for the Improvement of Higher Education Personnel (CAPES) (Projects: 88887.859244/2023-00, 88887.158285/2025-00).

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