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Atmospheric Chemistry and Physics Discussions

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Temperature variability and trend estimates at tropopause and UT-LS over a subtropical site: Reunion (20.8° S, 55.5° E)

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Abstract

This paper mainly focuses on the trends and variability of the tropopause and UT-LS temperature using radiosonde observations carried out over 16 years (January 1993 to December 2008) from a southern subtropical site, Reunion Island (20.8° S, 55.5° E), using a linear-regression fitting model. Two kinds of tropopause definitions, namely, cold point tropopause (CPT) and lapse rate tropopause (LRT) are used. In the purpose to characterize and quantify the relationship between the regional oceanic forcing and temperature at tropopause and UT-LS, we take into account the Indian Ocean Dipole (IOD) for the estimation of temperature trends. Results show that the main component is the Annual Oscillation (AO), particularly at tropopause (CPT, LRT) and in the lower stratosphere (LS) where more than 26% of the variability of temperature can be explained by AO. As a result, the influence of IOD on the variability of the temperature is at highest ratio at CPT and LS, with respectively 12.3% and 13.1%. The results show a low correlation between IOD and the temperature anomalies at tropopause (LRT, CPT) and UT-LS, in the range of 0.08–0.15, with the maximum of correlation at CPT (0.15). In addition, trend estimates at CPT and in the LS suggests that the IOD forcing contributes enhancing the rate of cooling of about 0.1 K per decade. Indeed a trend analysis reveals a cooling of about 0.90±0.40 K per decade at LS and a cooling trend of about 0.36±0.48 K per decade at CPT. The cooling trend at LS is found to be in good agreement with the others studies. These results support the assumption that the Indian Ocean may have a slight impact on temperature variability and on temperature change at CPT and in the LS over Reunion.

1 Introduction

Troposphere-lower stratosphere temperature in the Earth's atmosphere plays an important role in radiation budget and various chemical species understanding (Rosenlof et al., 2001; Bethan et al., 1996; Pan et al., 2004). The important aspect of studying

ACPD
10, 10113–10143, 2010

the troposphere and lower stratosphere temperature is a better understanding of the exchange of the trace constituent between the troposphere and stratosphere transport across the tropopause. Indeed the tropopause marks the transition between the troposphere and the stratosphere and it plays an important role in Stratosphere-Troposphere Exchange (STE) and wave propagation between the two regions (Holton et al., 1995; Baray et al., 1997; Sorensen and Nielsen, 2000).

In fact, studies on tropopause characteristics are further expected to provide climatology, to investigate variability and anomalies of thermal structures and tracers distributions, notably ozone and water vapour; as well as exchange processes that contribute to redistribution of these compounds on both vertical and horizontal scales. Since air enters the stratosphere mainly through the tropical tropopause, the latter plays therefore an importance role in the water vapour budget (and in other trace compounds, as well) in the stratosphere (Randel et al., 2000). Furthermore, it is well established that the seasonal cycle of water vapour entering the stratosphere is dominated by the seasonal cycle in temperature near the tropopause (Mote et al., 1996). At the tropical tropopause layer, temperature is a parameter controlling the input of water vapour from the troposphere and the dynamical properties of the region (Rosenlof et al., 2008). The annual variation is a fairly direct response to the annual variation in temperature of tropical surface insolation (Reid and Gage, 1981). Inter-annual variation in the tropopause temperatures have been linked to the quasi-biennial oscillation, El Niño and the episodic volcanic eruptions (Reid and Gage, 1985; Randel et al., 2000, 2004; Randel and Seidel, 2006). More recently, the presence of water vapour in the lower stratosphere and resulting changes in the ozone concentration/variability in the tropical tropopause have been highlighted by Randel et al. (2006). Moreover, studying Sea Surface Temperature (SST) anomalies in Western tropical Pacific Ocean, Rosensolf et al. (2008) noted a significant anti-correlation between the SST and the temperature anomalies of the tropical stratosphere, and concluded that the increased cooling may be an indication of tropical convection strengthening.

A series of extensive trend analyses of long-term record have shown a non-

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significant warming in the upper troposphere and a significant cooling in the lower stratosphere (∼1 K/dec), with a cooling (∼0.5 K/dec) at the tropopause (Ramaswamy et al., 2001; Bencherif et al., 2006; Seidel et al., 2001; Randel et al., 2000; Randel and Seidel, 2006; Oort and Liu, 1993). Based on the radiosonde datasets from 83 stations within the ±30° latitudinal belt from 1961 to 1990, Seidel et al. (2001) found also a cooling of ∼0.5 K per decade at the tropopause. More recently, over the southern tropics a study by Bencherif et al. (2006) showed a significant cooling in the lower stratosphere. In fact, they used 22-years of observational upper-air data recorded from 1980 to 2001 over Durban (30.0° S, 30.9° E), a South African site, and found a cooling of order 1.09±0.41 K per decade in the lower stratosphere.

A large number of remote sensing instruments exist to measure the atmospheric temperature: radiosonde, satellite, spectrometer, lidar, radar, etc. By method and cost, the measurements provided by the radiosonde are simple and effective tool to obtain the temperature profiles from ground up to ∼30 km height (Parker, 1985; Parker et al., 1997; Parker and Cox, 1995; Gaffen, 1993, 1996; Finger et al., 1995). Over the southern tropics and subtropics very few studies on UT-LS and tropopause characteristics are available because there are very few station. However, a limited number of stations are operating in the southern hemisphere tropics and subtropics under the SHADOZ (Southern Hemisphere ADditional OZonesondes) project since 1998 (Thompson et al., 2003). Reunion is one of these SHADOZ sites and offers one of the largest radiosonde-ozonesonde dataset in the southern tropics that goes back up to late 1992. Reunion is an overseas French Island in the Indian Ocean. It is an oceanic site located at 20.8° S in latitude and 55.5° E in longitude, at about 800 km east of Madagascar.

Recently, a tropospheric ozone climatology and trend study over Reunion has been reported by Clain et al. (2009) using this radiosonde-ozonesonde dataset. They found a positive trend of ozone (1.31±0.62 DU per decade) in the upper troposphere (10–16 km) from late 1992 to 2008. The results extended to the earlier ozone climatology reported over Reunion based on both radiosonde/ozonesonde and Satellite data sets (Sivakumar et al., 2007). The above study evidences the quality of the datasets used.

ACPD
10, 10113–10143, 2010

In this paper, we investigate trends and variability of the tropopause and UT-LS temperature by analysing 16 years (1993–2008) of radiosonde data recorded at Reunion with a linear-regression fitting model (referred hereafter as Trend-Run). Trend-Run is a statistical model adapted at Reunion University for temperature trend estimate in the southern subtropical UT-LS region (Bencherif et al., 2006). For the present study, the model has been modified by considering the regional oceanic forcing. In order to examine the impact of the regional oceanic forcing on the trend estimates at the tropopause and UT-LS layers temperature trends are estimated by taking into account the Indian Ocean Dipole (IOD).

The IOD corresponds to the inter-variability present into the Indian Ocean, with an east-west dipole in the SST anomalies of the basin. However the mechanisms responsible for the IOD are not yet well known but there are two assumptions. The first assumption is based on the fact that IOD is generated by a feedback coupled with ocean-atmosphere monsoon and the tropical circulation (Saji et al., 1999), whereas the second consider IOD as part of an Indo-Pacific ENSO (Behera et al., 2002). Motivation for taking into account that regional oceanic forcing is based on the results obtained by Rosenlof et al. (2008) over the Western tropical Pacific Ocean, as mentioned above.

Additionally, the present paper extends the first study on the tropopause characteristics over Reunion reported by Sivakumar et al. (2006). In fact, the present study aims to delineate the inter-annual variability and trend analysis based on a larger database and focusing on the temperature in the UT-LS region.

The paper is organized as follows: the next section provides a description of the data and the method used for linear trend calculation. Section 3 presents results obtained on temperature variability and trend results from the multi-regression Trend-Run model. The summary and the conclusions are given in Sect. 4.

ACPD
10, 10113–10143, 2010

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2 Data and methods

2.1 Data and definitions

The dataset used in this study is made of balloon-sonde temperature profiles recorded at Reunion by the OPAR (Observatoire de Physique de l'Atmosphère de la Réunion). It is a continuous and routine experiment that was initialized by end of 1992 with a fortnightly frequency under the NDACC (Network for the Detection of Atmospheric Composition Change) project. By January 1999 Reunion was included in the SHADOZ network, and the frequency of radiosonde experiment increased to become weekly. Details on the SHADOZ program are available from Thompson et al. (2003a, b, 2007).

Indeed, the Reunion radiosonde dataset is one of the longest time-series of ozone and temperature in the southern tropics. The present study uses 404 radiosonde temperature profiles recorded over 16 years period from January 1993 to December 2008. Figure 1 illustrates the monthly cumulative distributions of the number of balloon-sonde launched at Reunion and used for the present study. The total number of profiles is ranging between 21 and 38 per month. It corresponds therefore to 16 years of continuous and homogenous observations. In this study, we have interpolated the measured radiosonde temperature profiles into 50 m vertical resolution in the height range from 0 to 30 km.

A radiosonde set carries three different sensors to measure in situ parameters, i.e., pressure, temperature and relative humidity. In order to measure the associated partial pressure of ozone, an Electrochemical Concentration Cell is added. Radiosonde experiments enable measurements of temperature profiles from ground up to the burst altitude of the balloon, which is at ~30–35 km. At Reunion station, Väisälä RS80 sondes had been used until October 2006. By 2007 the radiosonde experimental set was upgraded. Since then the Modem-M2K2 system has been used together with the Väisälä RS90 sondes.

In order to check the quality of the data, the Reunion radiosonde system was part of the JOSIE (Julich Ozone-Sonde Intercomparison Experiment) process. That inter-

ACPD

10, 10113–10143, 2010

Trends and variability of the tropopause and UT-LS temperature

N. Bègue et al.

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comparison campaign is conducted under the aegis of the World Meteorology Organization with the purpose to assess the performances of radiosonde systems through intercomparison with a standard reference instrument (Thompson et al., 2007).

The present study aims to examine temporal evolution of temperature at the tropopause and in the UT-LS. The tropopause is examined in terms of the Lapse Rate Tropopause (LRT) and the Cold Point Tropopause (CPT); while the Lower Stratosphere (LS) is examined in terms of the averaged temperature between 18 and 19 km layer and the Upper Troposphere (UT) is examined in terms of the averaged temperature between 14 and 15 km layer. The tropical Cold Point Tropopause is a key parameter that controls the entrance of tropospheric air into the stratosphere and particularly for the water vapour (Randel et al., 2006; Rosenlof et al., 2008). It is defined as the height where the minimum temperature is found below 20 km. The Lapse Rate Tropopause represents the standard World Meteorology Organization definition of the tropopause. It corresponds to a temperature lapse rate decreasing and not exceeding 2 K km^{-1} through a 2-km deep layer (WMO, 1957). Besides to discontinuity in lapse rate at tropopause, it acts as a dynamical barrier/filter on tropospheric vertical motions.

2.2 The Trend-Run model

Trend analyses are based on a linear regression fitting model called Trend-Run. It is an adaptation from the AMOUNTS (Adaptive MOdel UNambiguous Trend Survey) and AMOUNTS-O3 models developed for ozone and temperature trend assessments (Hauchecorne et al., 1991; Keckhut et al., 1995; Guirlet et al., 2000). The Trend-Run is hence a statistical model that has been adapted and used at Reunion University for temperature trend estimate in the southern subtropical UTLS (Bencherif et al., 2006). The model lean on the principle of breaking down the variations of a time series $Y(t)$ into the sum of the different forcings that govern the variations of $Y(t)$:

$$Y(z,t) = c_1\mathrm{SAO}(z,t) + c_2\mathrm{AO}(z,t) + c_3\mathrm{QBO}(z,t) + c_4\mathrm{ENSO}(z,t) + c_5\mathrm{SSN}(z,t) + \varepsilon \quad (1)$$

where ε is the residual term assumed to be made up of trend and noise.

ACPD
10, 10113–10143, 2010

When the coefficients $c_{i(i=1\,\mathrm{to}\,5)}$ are calculated, the corresponding forcings are removed from the studied geophysical signal $Y(t)$. The model applies then the least-square method in order to minimize the residual sum of squares and to retrieve the forcing coefficients c_i. Regarding the trend, it is parameterised as linear: $\mathrm{Trend}(t)=\alpha_0+\alpha_1.t$, where t denotes the time range, α_0 is a constant, α_1 is the slope of $\mathrm{Trend}(t)$ line that estimates the trend over time scale.

In its initial version, as used by Bencherif et al. (2006), the Trend-Run model considers the mean forcings, i.e., annual and semi-annual cycles, QBO (quasi-biennal oscillation), ENSO (El-Nino Southern Oscillation), and the 11-years solar cycle (SSN). Annual and Semi-Annual Oscillations (AO, SAO) are taken into account as the mean seasonal cycles. Moreover, we used the monthly mean zonal wind speed at Singapore at 40-hPa level and the South Ocean Index to parameterize respectively the QBO (Randel et al., 1994; Li et al., 2008) and the ENSO cycles; while the 11-year solar cycle is defined as a linear function correlated with the solar flux at 10.7 cm.

In order to examine the hypothetic link between the regional oceanic forcing and temperature trend estimate at tropopause and UT-LS layer, the Trend-Run model has been modified by introducing the Indian Ocean Dipole (IOD).

Then, the model equation turns into:

$$\begin{aligned} Y(z,t) &= c_1\mathrm{SAO}(z,t)+c_2\mathrm{AO}(z,t)+c_3\mathrm{QBO}(z,t) \\ &\quad + c_4\mathrm{ENSO}(z,t)+c_5\mathrm{SSN}(z,t)+c_6\mathrm{IOD}(z,t)+\varepsilon \end{aligned} \tag{2}$$

Motivation for including the IOD as a potential forcing on the change at tropopause and UT-LS is based on the fact that ocean-atmosphere interactions, through convective activity, are believed to play an important role in climate change (Saji et al., 1999; Yamagata et al., 2004). Recently, Rosenlof et al. (2008) examined trends in the temperature of the tropical lower stratosphere from several radiosonde sites in the western tropical Pacific Ocean. Their result suggests that sea surface anomalies have an influence on temperature variations at the tropopause and in the lower stratosphere. Similarly, we intend in the present trend estimation to examine effects of Indian Ocean

ACPD
10, 10113–10143, 2010

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anomalies over Indian Ocean region by introducing the IOD. The IOD is characterized by a positive phase when SST (Sea Surface Temperature) is anomalously cooling in the eastern equatorial Indian Ocean and anomalously warming in the western equatorial Indian Ocean, and with a negative phase when the conditions are opposite (Behera et al., 2002). The IOD is commonly measured by an index called the Dipole Mode Index (DMI), which it is defined as the SST anomaly difference between western (50° E–70° E, 10° S–10° N) and eastern (90° E–110° E, 10° S-Equator) tropical Indian Ocean. In order to consider IOD in the Trend-Run model, we used DMI from http://www.jamstec.go.jp/frsgc/research/d1/iod.

3 Results and discussion

3.1 Monthly climatological temperature

For trend estimation, temperature profiles have been reduced into monthly averaged profiles. Figure 2 shows the resultant time-height cross-section, with the corresponding thermal tropopause (LRT, CPT) height superimposed. One can notice that some profiles are vertically limited and others are missed due to technical or unfavourable meteorological conditions. The ratio of missed monthly profiles is estimated at ∼22%. Moreover, this figure confirms the fact that the tropopause is not a static layer of the atmosphere. Indeed the Fig. 2 illustrates the inter-annual variability of the thermal tropopause height from January 1993 to December 2008. In order to fill the gaps we compute and use the monthly climatological temperatures at UT, LRT, CPT and LS derived from Reunion dataset covering this period.

The monthly climatological temperature values and the corresponding standard deviation are depicted in Fig. 3 and reported in Table 1. Figure 3a shows that seasonal variations of temperature at CPT and LRT are well correlated (0.97), and the CPT appears on average 2 K colder than the LRT. The minimum temperatures at CPT and LRT are 193.9 K and 195.8 K, respectively, and both appear during austral summer

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(December–February), whereas the maximum temperature appears during September with respectively 198.6 K and 200.3 K. Furthermore, Fig. 3a shows a dominant annual cycle at LRT, CPT and LS heights over Reunion Island. This is in agreement with results obtained by Bencherif et al. (2006) for Durban (30.0° S, 30.9° E). They reported on temperature climatology and trend estimate by the use of a 22-year upper-air dataset, and found that the annual oscillation is the most dominant forcing with maximum amplitude at tropopause height and in the lower stratosphere. Figure 3a shows that at UT the annual cycle is less important than for the upper layers (LRT, CPT and LS). Figure 3b shows that seasonal variations of CPT and LRT heights are much correlated (0.84) but the CPT appears on average 0.91±0.15 km higher than the LRT. This is in agreement with results reported earlier by Sivakumar et al. (2006) for Reunion where they found that the CPT appears 1.09±0.94 km higher than the LRT. The CPT and LRT are the lowest (CPT at 16.8 km and LRT at 15.9 km) by September, while, they are at the highest (CPT at 17.4 km and LRT at 16.7 km) during the austral summer. The obtained monthly variations over Reunion are quite similar to the results obtained by Seidel et al. (2001). In fact, based on the radiosonde datasets from 83 stations within the ±30° latitudinal belt from 1961 to 1990, Seidel et al. (2001) found that tropopause is the highest (about 17 km) and the coldest (about 191 K) during the austral summer, while it is the lowest (about 16.3 km) and the warmest (about 195 K) during the austral winter.

3.2 Temperature variability

A statistic parameter that is used to quantify how well the regression fitting model describes the data is the coefficient of determination R^2. It is defined as the ratio of regression sum of squares to the total sum of squares. The coefficient of determination measures the proportion of the total variation in time-series of temperature that is explained by the regression model. If the regression model explains very well the total variation in the geophysical signal $Y(t)$, the value of R^2 is near to unit; but, on the opposite, when the model does not resolve all the variations, R^2 tends to zero (Pas-

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tel et al., 2007). Figure 4 depicts the time-evolution of mean monthly temperature at CPT over Reunion from radiosonde observations (in blue line) and the corresponding simulation from the Trend-Run regression model (in red line). The coefficient of determination obtained for CPT variations is high, i.e., ~0.80, and suggests that the model is reproducing well most of the variability of the studied temperature signal.

Table 2 summarizes values of contribution coefficients c_i for SAO, AO, QBO, IOD, ENSO and SSN forcing, together with values of coefficient of determination R^2 at UT, CPT, LRT and LS. All corresponding coefficients of determination are higher than 0.70, except the one for UT layer: R^2(UT)=0.52. The highest value 0.80 is obtained at CPT, while R^2 is ~0.78 and ~0.73 at LRT and LS, respectively. This suggests that the regression model Trend-Run explains quite well the variability of the temperature time series. As some geophysical processes, such as the volcanic aerosol loading, are not considered within the model, obviously part of the variability could not be explained.

As expected, the most dominant component in the thermal structures in the local UT-LS is the AO. In fact, AO is found to explain more than 26% of the variation of temperature at LRT, CPT and LS. The influence of the AO on the variation of temperature is maximum at LRT (45.0%). Regarding the SAO, its maximum influence, i.e. 10.2%, is located at LRT. As one may expect in the UT-LS region, the influence of the AO on the variation of temperature is about 3–4 times stronger than the influence of the SAO. This is in agreement with results obtained over Durban using 22-years of observational upper-air data recorded from 1980 to 2001 over Durban (Bencherif et al., 2006). Indeed, the seasonal variations of temperature at the tropopause over Reunion are mostly driven by the AO with the coldest temperature and the highest tropopause height during the austral summer and the warmest temperature with the lowest tropopause height during the austral winter (Fig. 3a, b). However, this table shows that the cumulative influence of the oceanic forcings (IOD and ENSO) is quite important. Indeed about 12.1% of the variation of temperature is explained by ENSO versus about 10.5% by AO at UT.

From Trend-Run analyses, about 10% of temperature variability at tropopause may

ACPD
10, 10113–10143, 2010

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◂◂ ▸▸
◂ ▸
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

be explained by the QBO forcing (see Table 2). This result is relatively in agreement with the one obtained by Randel et al. (2000) for the inter-annual variability of the tropical tropopause derived from radiosonde of 26 stations and NCEP reanalyses (period: 1979–1997). They found that 12% of the inter-annual variance of the tropopause temperature is explained by the QBO. Nevertheless, in the lower stratosphere, the QBO contributes for ∼6.2% to temperature variability, less than at LRT and CPT.

Two oceanic forcings are included in our regression model: the ENSO and the IOD forcings. The highest contribution of ENSO and IOD is found at CPT and LS: ENSO and IOD explain respectively 12.3% and 13.1% of the inter-annual variability of temperature. They hence admit contributions larger than that of the QBO at these two layers. However, this table shows that 12.1% of the inter-annual variability of temperature at UT is explained by ENSO. This result is in agreement with past works reported by Reid and Gage (1985). They showed that inter-annual variations in the tropical tropopause are linked to the ENSO. Besides, this result suggests that CPT and LS have significant connections with the underlying sea surface forcing. This is consistent with the funding from Rosenlof et al. (2008). Indeed, Rosenlof et al. (2008) examined trends in the temperature of the tropical lower stratosphere from several radiosonde sites on the so-called warm pool region of the western tropical Pacific Ocean. They found a significant anti-correlation between the stratospheric temperature anomalies and sea surface temperature anomalies in the western tropical Pacific Ocean and they concluded that convection may therefore be a link between the ocean and the LS. In our case, the result strongly suggests that the underlying Indian Ocean can have a fairly influence on the temperature variability at CPT and LS layers.

In the second step of our analysis, the seasonal cycle (SAO, AO) has been removed in order to emphasize the signature of the other parameters, particularly the signature of the two oceanic forcings at CPT and LS. The differences between the mean monthly temperature and the monthly climatology temperature (mentioned at 3.1) represent the deseasonalised monthly means, referred to as "temperature anomalies" hereafter. Figure 5a shows that IOD (in red line) and the temperature anomalies at CPT (in blue

ACPD
10, 10113–10143, 2010

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line) are slightly correlated (0.15), whereas ENSO and the temperature anomalies at CPT are slightly anti-correlated (−0.20) (Fig. 5b). The same analysis has been realized for the other layers. The results obtained show that IOD and the temperature anomalies at tropopause (LRT, CPT), and overall the UT-LS, are slightly correlated, in the range of 0.08–0.15, with the maximum of correlation at CPT. As a result, for ENSO, we obtained a low anti-correlation in the range of 0.06–0.21 for the tropopause and UT layers, with the maximum of anti-correlation at UT (−0.21), whereas ENSO and the temperature anomalies at LS are slightly correlated (0.10). Similarly, as reported by Rosenlof et al. (2008), the cross correlation between the monthly temperature anomalies at the 70 hPa level (LS) over Koror (7.3° N, 134.5° E) and the SST anomalies of the equatorial western Pacific warm pool in the 1960–1993 period is about −0.15.

Reunion observations and results suggest that the inter-annual variation of temperature at tropopause and broadly in the subtropical UT-LS is slightly linked to the oceanic forcings.

3.3 Linear trend estimates

The aerosols constitute a source of uncertainty which may affect the temperature trend estimate, notably following a major volcanic eruption, because of their role in the thermal balance. The eruption of Pinatubo in June 1991 caused the largest perturbation of the 20th century in the stratosphere (McCormick et al., 1995). A 1 K global temperature increase in the lower stratospheric at 50 hPa was observed after the eruptions of El Chichón and Pinatubo (WMO, 2006). Bencherif et al. (2003) showed from SAGE II data that the volcanic aerosol amount in the southern subtropical UT-LS decreased gradually to return to its normal level by late 1995 and early 1996. Consequently, in order to avoid introducing bias in temperature trend estimates due to aerosol loading, the post-Pinatubo temperature values (January 1993–December 1995) have been discarded, reducing thereby the trend analysis to the period from January 1996 to December 2008. However, in order to examine the impact of the IOD and volcanic aerosols on the temperature trend estimates, the regression model Trend-Run is used following different schemes: with or without IOD forcing, and with or without the post-Pinatubo dataset.

Figure 6 depicts the time evolution of mean monthly temperature in the LS with and without post-Pinatubo dataset over Reunion, with the cooling trend lines superimposed. This figure illustrates a cooling more important with post-Pinatubo dataset (−1.31±0.33 K per decade) than without post-Pinatubo dataset (−0.90±0.40 K per decade). Additionally, this result highlights a significant cooling in the lower stratosphere over Reunion.

This cooling in the lower stratosphere is quite similar to results obtained by Bencherif et al. (2006) for Durban (30.0° S, 30.9° E). Based on 22 year period temperature radiosonde data, they found that the maximum cooling rate is 1.09±0.41 K per decade, and is observed in the lower stratosphere, at 70 hPa. Moreover, the significant cooling in the lower stratosphere is in agreement with other studies (Oort and Liu, 1993; Angell, 1988). Based on the global rawinsonde network of more than 700 stations, Oort and Liu have found a significant cooling of order −0.43±0.16 K per decade in the lower stratosphere (period: 1964–1988).

Table 3 shows temperature trends in the UT-LS obtained with and without including the IOD forcing in the model, and with and without taking into account the post-Pinatubo data. The first column shows temperature trends obtained at UT, LRT, CPT and LS with IOD and post-Pinatubo data includes; the second column is similar to the first one but without IOD; and the third column is also similar to the first one but without taking into account the post-Pinatubo data. Note that in all situations, the model has a good coefficient of determination R^2, i.e., R^2 is within 0.73 and 0.80, except at UT where R^2 is relatively weak (∼0.52). The results confirm the possibility that trend analyses may be biased by the post-Pinatubo dataset if not removed, notably in the LS. Indeed, in the LS difference in temperature trends, when post-Pinatubo data are taken into account or not, is in the range of 0.32–0.41 K/decade (Table 3). However, the results show that at CPT the difference between temperature trends with and without taking into account the post-Pinatubo data is weak: ∼0.02 K per decade. Moreover, Randel et al. (2000)

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showed that the effect of Pinatubo is less distinctive at the tropopause, particularly in the radiosonde average, and it is difficult to isolate in individual station record.

In general, the Table 3 highlights a cooling in the LS, tropopause and UT. However, temperature trends obtained at tropopause (CPT, LRT) and at UT are not significant except for calculation of trend with IOD and post-Pinatubo data, probably because of the length of the data. Tiao et al. (1990) have shown that the precision of trend determination depends critically on variability of the individual observations, on the autocorrelation in the observation and on the length of the data record. In fact, our result shows a non-significant warming trend at LRT of order 0.12±0.39 K per decade. Seidel et al. (2001) showed from radiosonde data recorded at 20 stations within ±15° for the period 1978–1997 a cooling of about 0.5 K per decade at LRT. However, they found at Kato Kinabalu (5.9° N, 116.1° E) a positive trend at LRT of order 0.11 K per decade. In addition, Randel et al. (2000) with radiosonde data found negative trends of −0.5 K per decade during 1979–1997 at LRT, whereas they found with NCEP data a non-significant positive trend at LRT of about 0.04±0.22 K per decade during the same period. In the same way, our results show a non-significant cooling trend at UT: 0.12±0.35 K per decade. Furthermore, Oort et al. (1993) considered the long-term trends from global rawinsonde network (period: 1964–1988). They obtained a cooling trend: 0.11±0.11 K per decade at UT in the south hemisphere. Recently, Bencherif et al. (2006) showed from radiosonde data at Durban for the period 1980–2001 a cooling of about 0.10±0.18 K per decade at UT.

It is however clear from Table 3 that only temperature trend in the lower stratosphere is significant for both situations with or without post-Pinatubo data. We obtain respectively a cooling of about −1.31±0.33 K per decade and −0.90±0.40 K per decade with and without post-Pinatubo data. From that table it can be seen that at LRT there is almost no difference between temperature trends with and without IOD, whereas at CPT and LS results are different. In fact, in the LS and at CPT, whether the IOD is taken into account or not, we have a difference of ∼0.08 K per decade at CPT and ∼0.19 K per decade in the lower stratosphere.

ACPD
10, 10113–10143, 2010

This result corroborates the IOD effect on temperature variability and trend estimates at CPT and in the LS, and suggests that the IOD forcing contributes enhancing the rate of cooling of about 0.1 K per decade. Consequently one can say that IOD should be taken into account for the calculation of temperature trends in the LS and at CPT. These results support the assumption that the Indian Ocean can have impact on temperature variability and change at tropopause and in the LS.

4 Summary and conclusion

This paper deals with trends and variability of the tropopause and UT-LS temperature over a southern subtropical site. The study mainly focuses on analysis of temperature profiles derived from balloon-sonde experiments at Reunion (20.8° S, 55.5° E) during the January 1993–December 2008 period. The Reunion dataset is an original and useful one to study tropopause and UT-LS characteristics and changes. There is in fact a very few operating sites in the southern tropics, and the Reunion dataset is the longest one.

Trend analyses are based on a linear multi-regression fitting model called Trend-Run. The general purpose of the use of multi-parameter regression analysis is to examine impact of several geophysical cycles and forcings on the variability thermal structures at tropopause and broadly the observed subtropical UT-LS region. In order to examine a possible links between the Indian Ocean forcing and temperature trend estimate, the Trend-Run model has been modified to take into account the IOD forcing. Indeed the IOD represents the inter-annual variability present in the Indian Ocean with an east-west dipole in the SST anomaly of the basin. As a result, more than 70% of the variability of temperature at tropopause (CPT, LRT) and in the LS is reproduced by the Trend-Run model.

Our results show that the AO is the main component in the variability of temperature at tropopause and UT-LS temperature over Reunion. In fact more than 26% of the variation of temperature at tropopause and in the LS can be explained by AO. Furthermore, we note that the influence of IOD on the variability of temperature is at the highest ratio at CPT and LS. In fact, at CPT, 12.3% of the variation of temperature can be explained by IOD, whereas at LS, this increases to 13.1%. This result suggests that the underlying Indian Ocean can have an influence on the variability of the thermal structures at CPT and LS.

In the present study, the Trend-Run model is applied to selected layers and heights in the UT-LS region: UT, LRT, CPT and LS. The trends estimates are examined with or without including IOD and post-Pinatubo data. Temperature trends at tropopause and UT are not significant except for the calculation with the full dataset, i.e., with post-Pinatubo. This result confirms the fact that the precision of trend determination may depend on aerosol loading in the UT-LS and on the length of the data record (Kerzenmacher et al., 2006). However the temperature trend in the LS obtained is significant for both cases with and without post-Pinatubo. The temperature trends obtained show a significant cooling of the LS and a non-significant cooling of the UT over Reunion. As a result, we observed a cooling trend (0.36±0.48 K per decade) at CPT, while LRT exhibited a warming trend (0.12±0.39 K per decade).

The results obtained for temperature trends confirm the possibility that trend analyses over Reunion may be biased if post-Pinatubo data are not removed or adjusted for volcanic influence. Indeed we note a difference in temperature trend estimate when post-Pinatubo data are taken into account or not: in the range of 0.32–0.41 K per decade. Furthermore, the analysis of temperature trends with and without IOD at CPT and LS suggests that the IOD forcing contributes enhancing the rate of cooling of about 0.1 K per decade.

Finally, this multi-parameters regression analysis has shown that the sea surface forcing due to the underlying Indian Ocean may influence the variation of temperature at CPT and LS layers. This result is found to be in agreement with the fact that cooling of the tropical LS is a dynamical result of tropospheric convection, which in turn partially depends upon SST anomalies.

ACPD
10, 10113–10143, 2010

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ACPD

10, 10113–10143, 2010

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◀| |▶

◀ ▶

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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ACPD
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Trends and variability of the tropopause and UT-LS temperature

N. Bègue et al.

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Table 1. Monthly mean climatological temperature and corresponding standard deviations (in Kelvin) at UT, LRT, CPT and LS from radiosonde data collected at Reunion from January 1993 to December 2008.

	UT 14–15 km (K)	LRT (K)	CPT (K)	LS 18–19 km (K)
January	205.1±2.2	195.8±1.8	193.9±2.3	197.2±3.7
February	205.3±2.0	195.3±2.7	193.4±3.0	197.6±2.7
March	205.5±1.7	196.0±1.9	193.9±1.6	197.4±1.8
April	205.9±1.6	196.9±2.6	195.4±2.6	198.5±1.7
May	207.1±1.4	198.3±3.4	195.3±1.2	198.2±2.1
June	206.9±1.5	198.1±1.6	196.1±1.1	200.3±1.3
July	206.4±1.4	198.1±1.6	196.2±0.8	201.0±1.5
August	206.7±1.7	198.7±1.7	197.0±1.5	202.4±1.5
September	206.7±2.7	200.3±1.6	198.6±2.0	202.3±3.0
October	207.1±2.2	199.4±1.5	197.6±1.3	202.0±1.7
November	206.6±1.3	198.7±2.5	196.7±2.1	199.1±1.9
December	204.6±1.8	196.9±1.7	194.7±0.9	199.2±1.2

ACPD

10, 10113–10143, 2010

Table 2. Contribution percentages of SAO, AO, QBO, IOD, ENSO and 11-year solar cycle to temperature variability at UT (14–15 km), LRT, CPT and in the LS (18–19 km), as obtained by the linear regression Trend-Run model. The last line gives the corresponding values for the coefficient of determination, R^2.

	UT 14–15 km (%)	LRT (%)	CPT (%)	LS 18–19 km (%)
SAO	5.5	10.2	8.1	9.1
AO	10.5	45.0	32.0	26.0
QBO	4.9	9.6	11.2	6.2
IOD	4.4	6.0	12.3	13.1
ENSO	12.1	5.2	13.0	11.2
SSN	14.6	2.0	3.4	8.4
R^2	0.52	0.78	0.80	0.74

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ACPD
10, 10113–10143, 2010

Trends and variability of the tropopause and UT-LS temperature

N. Bègue et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 3. Temperature trends (in Kelvin per decade) at UT, LRT, CPT and LST as computed by the Trend-Run model from radiosonde observations at Reunion Island. The model takes into account AO, SAO, QBO, ENSO and 11-year solar cycle. This table illustrates temperature trends with (first column) and without (second column) including the IOD forcing in the model, and with and without taking into account the post-Pinatubo data. The averaged coefficient of determination R^2 is about 0.75. The Pinatubo tests (last column) are made with the IOD included.

	with IOD + Pinatubo	without IOD	without Pinatubo
LS	−1.31±0.33	−1.22±0.33	−0.90±0.40
CPT	−0.38±0.33	−0.30±0.34	−0.36±0.48
LRT	−0.52±0.35	−0.49±0.35	+0.12±0.39
UT	−0.37±0.27	−0.34±0.27	−0.12±0.35

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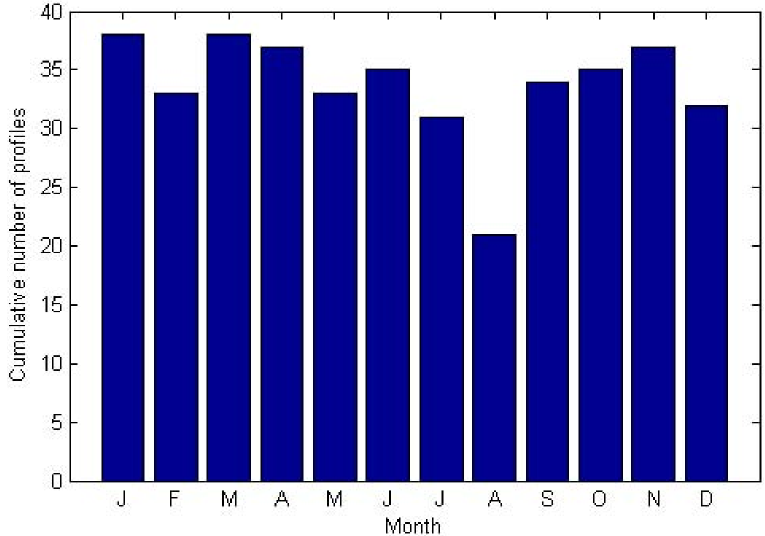

Fig. 1. Cumulative monthly distributions of radiosonde profiles from January 1993 to December 2008 recorded at Reunion Island.

ACPD

10, 10113–10143, 2010

Trends and variability of the tropopause and UT-LS temperature

N. Bègue et al.

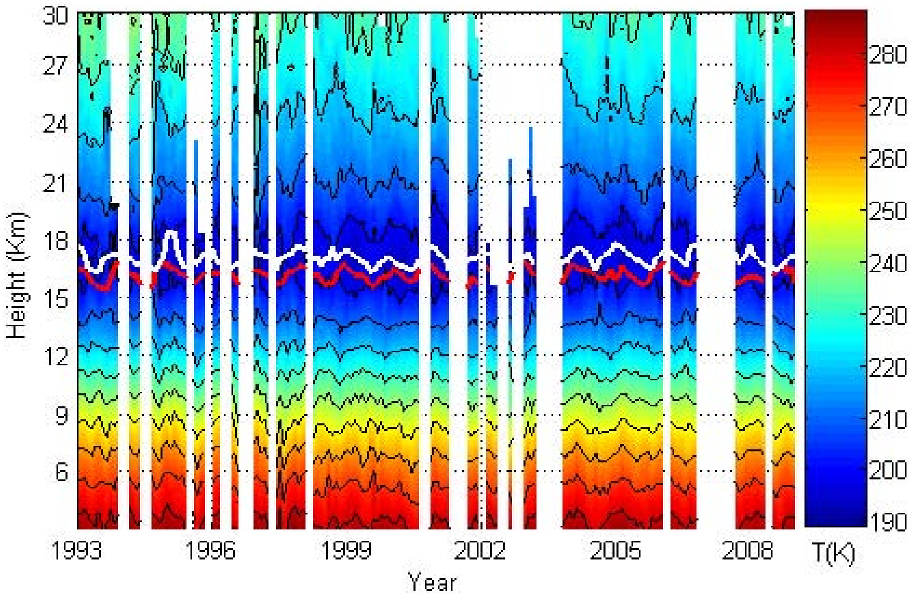

Fig. 2. Evolution of the temperature time series from January 1993 to December 2008 over Reunion with CPT (white) and LRT (red).

ACPD
10, 10113–10143, 2010

Trends and variability of the tropopause and UT-LS temperature

N. Bègue et al.

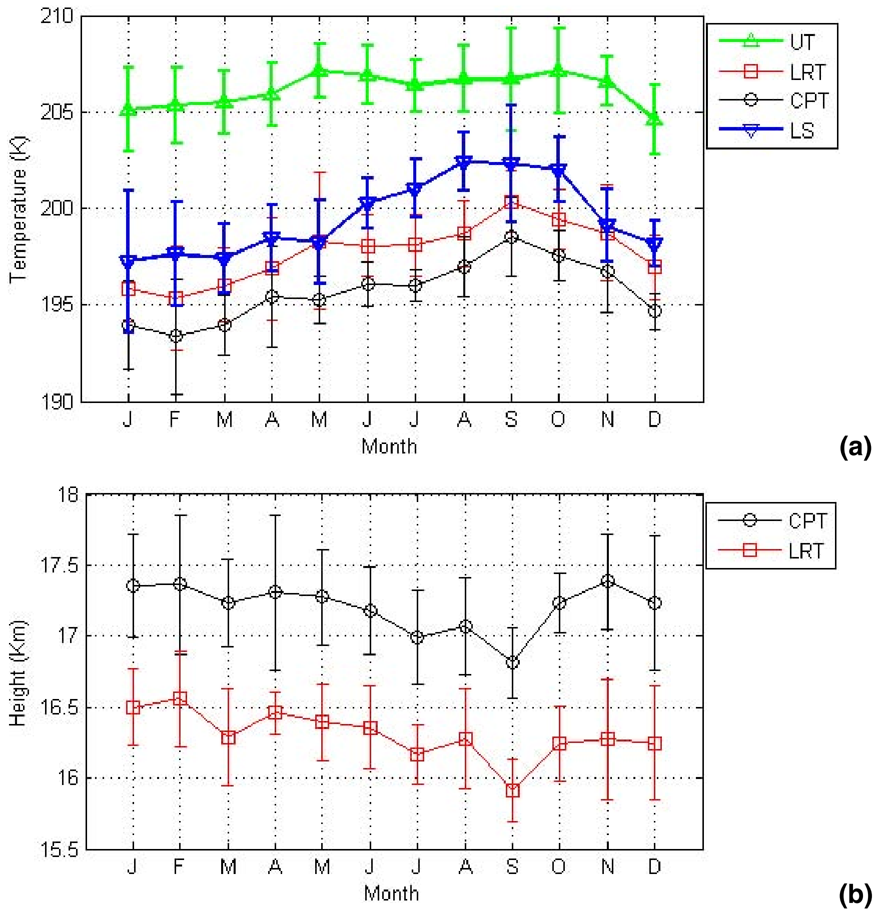

Fig. 3. **(a)** Time evolution of monthly averaged temperature at UT, LRT, CPT and LS over Reunion derived from continuous observations during the period from January 1993 to December 2008. **(b)** Time evolution of monthly averaged heights of LRT and CPT over Reunion from the same period of observations as (a).

ACPD
10, 10113–10143, 2010

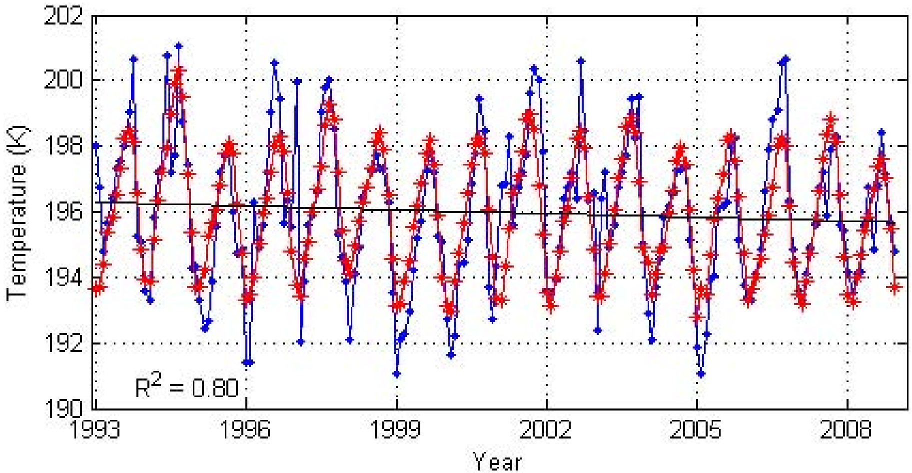

Fig. 4. Time evolution of monthly temperature values as observed over Reunion Island at CPT from January 1993 to December 2008 (blue line), the superimposed red star line represents CPT values as simulated by Trend-Run regression model, while the straight black line illustrates the obtained temperature trend at CPT. The corresponding coefficient of determination R^2 is showed, R^2=0.80.

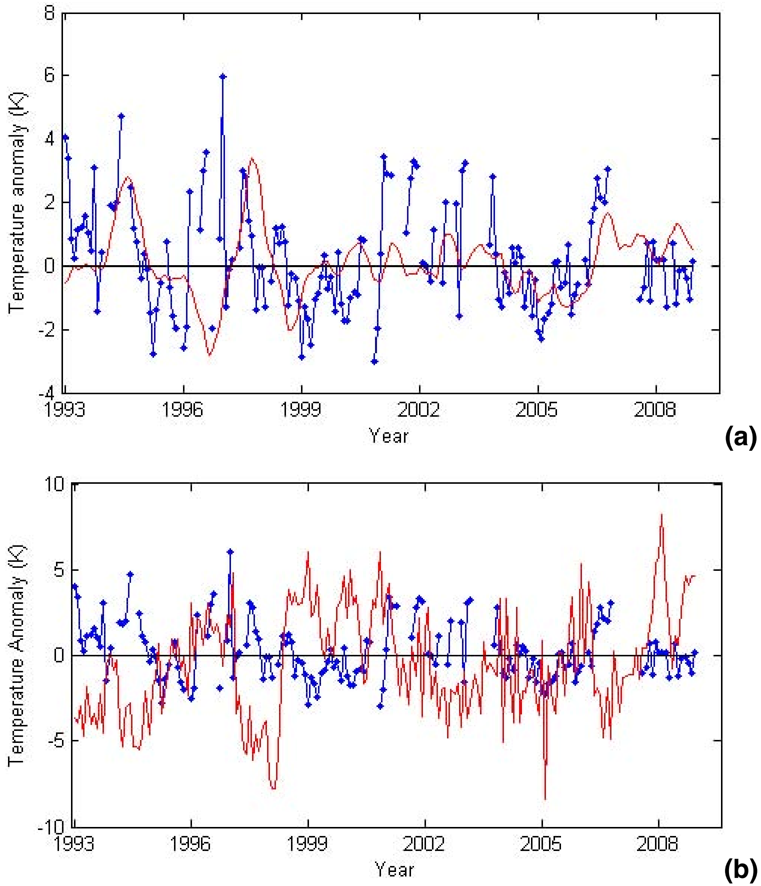

Fig. 5. Time evolution of deseasonalised monthly averaged temperature at CPT (blue line) over Reunion derived from continuous observations during the period from January 1993 to December together with **(a)** Indian Ocean Dipole (IOD) component as parametrized in the regression analysis (red line) and with **(b)** ENSO component as parametrized in regression analysis (red line).

ACPD
10, 10113–10143, 2010

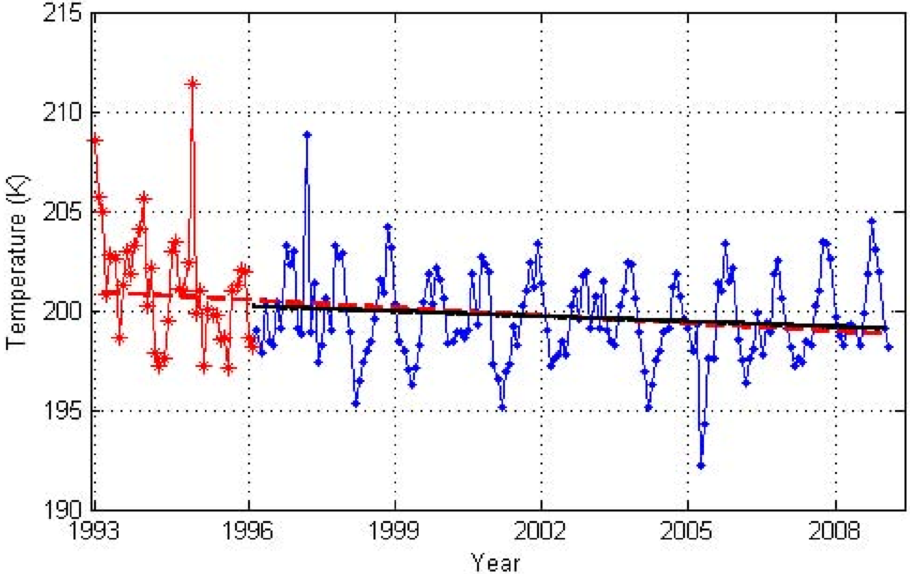

Fig. 6. Time evolution of the monthly averaged temperature values in the lower stratosphere (18–19 km) with the post-Pinatubo data (red star line) and the without post-Pinatubo data (blue line). The superimposed cooling trend line obtained with the post-Pinatubo data (dash red line) and the cooling trend line obtained without the post-Pinatubo data (black line).

ACPD
10, 10113–10143, 2010

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion