Impacts of Stratospheric Sudden Warming Event on Tropical Clouds and Moisture Fields in the TTL: A Case Study

Nawo Eguchi1 and Kunihiko Kodera2,3
1National Institute for Environmental Studies, Tsukuba, Japan
2Nagoya University, Nagoya, Japan
3Meteorological Research Institute, Tsukuba, Japan

Abstract

The impact of stratospheric sudden warming event in September 2007 on the tropics was investigated based on satellite data (CALIOP, MLS and TRMM PR). Equatorial temperature and water vapor at 100 hPa decreased by about 1 K and 1 ppmv within 10 days, respectively. Changes in tropical clouds are observed together with the occurrence of the SSW as i) frequent formation of higher-level cirrus clouds over the Maritime Continent, to where water vapor was transported from Asian Monsoon and where the lowest temperature occurred, ii) intensification of deep convective activity in the TTL over African continent, and iii) southward shift of the convective clouds over South American continent.

1. Introduction

It is known that stratospheric sudden warming (SSW) influences the tropical stratosphere via changes in Brewer-Dobson circulation (e.g., Andrews et al. 1987). However, the results of recent studies on SSW that occurred in the Southern Hemisphere (SH) during September 2002 (Kodera and Yamada 2004; Eguchi and Kodera 2007) suggest that cooling of the tropical tropopause layer (TTL, e.g., Fueglistaler et al. 2009) due to SSW not only results in the formation of cirrus clouds, but also modifies large-scale deep convective activity via changes in mass and water-vapor convergences. A similar influence has been reported for SSW in the Northern Hemisphere (NH) (Kodera 2006), although it was not possible to obtain further details because of a lack of information regarding the detailed vertical structure of clouds in the TTL.

Cirrus clouds play an important role in terms of the radiative balance in the TTL and water-vapor transport to the stratosphere (e.g. Liou 1986; Ramanathan and Collins 1991). Furthermore, cirrus clouds are regarded as an indicator of change in the temperature field arising from dynamical changes in the stratosphere and troposphere (e.g., Eguchi and Shiotani 2004; Immel et al. 2008; Sassen et al. 2008). However, the mechanism of the global-scale cirrus formation remains poorly understood. In this respect, important information can be gained from analyses of the global distribution of cirrus clouds and deep convective activity during SSW events. The present study conducted a case study on a SSW in the SH during September 2007 (hereafter SSW07) to clarify the changes of cirrus and convective clouds in the TTL associated with the SSW by using the recent measurement data from a satellite lidar housed aboard the Cloud Aerosol Lidar with Orthogonal Polarization (CALIOP) satellite (Winker et al. 2007), including the top and bottom heights of cloud layer, optical thickness (τ), and the number of cloud layers based on measurements with an along-track resolution of 5 km. Here, cirrus clouds are defined as having a geometric thickness of 3 km or less and τ of 3 or less. In addition, the bottom altitude must exceed 8 km in the tropics (15°S–15°N) or 5 km in the extra-tropics. These thresholds are from Eguchi et al. (2007). In the case that the ground was not detected in a profile, we did not consider data from the lowest cloud layer. The cirrus frequency at 5° (or 10°) × 5° grid box is defined by the ratio of cirrus data to all data which could detect the surface within the grid box.

Vertical profiles of precipitation obtained by a precipitation radar housed aboard the Tropical Rainfall Measuring Mission (TRMM PR) (Kummerow et al. 2000) were used to investigate convective activity and vertical structure of convective clouds after transforming orbital data to 5° × 5° gridded data. Meteorological variables, such as temperature, were obtained from the National Centers for Environmental Prediction (NCEP) reanalysis data. For water vapor in the TTL, we used EOS MLS water vapor data (Read et al. 2007) at 100 hPa.

3. Results

Time series of eddy heat flux at 100 hPa averaged over 45°S to 75°S latitudes shown in Fig. 1a during the period of 25 August to 6 October 2007, and anomalous south polar temperature at 10 hPa (90°S–60°S) and tropical temperature at 100 hPa (30°S–30°N) are displayed in Fig. 1b. It can be seen that due to the amplification of the planetary wave poleward (negative) eddy heat flux increased in mid-September which led to a sudden warming in the SH. It is suggested that the intensified B–D circulation also created a lower temperature over the tropical stratosphere (Kodera and Yamada 2004).

Figure 1d shows the height-time section of the anomalous zonal mean temperature over the equator for the same period as in Figs. 1a and 1b. The tropical temperature above the 150 hPa pressure level shows a rapid decrease at all heights in the stratosphere after 16 September. Here, 16 September is defined as the onset day of the equatorial impact of SSW07. To investigate the effect of SSW, we calculated the differences between the 10-day means before onset (period A: 6–15 September) and after onset (period B: 16–25 September).

Figures 2a and 2b show the 100 hPa temperature at periods A and B. Note that the seasonal march is included in Fig. 2. The temperature shows a zonal mean decrease along the equator by about 1 K, but the decrease exceeds 2 K over the area between the east coast of Africa and the Maritime Continent, and South America (Fig. 3a). The horizontal distribution of the occurrence frequency [%] of cirrus cloud with the top height of 14 km or higher is shown in Figs. 2c and 2d. Cirrus clouds occur frequently over the cold region from South Asia to the Maritime Continent and over the equatorial South American and African continents at period A. Cirrus clouds show an increase in the tropics as shown.
Figures 2e and 2f show average precipitation intensity in the TTL (14–18 km) for periods A and B, similar to Figs. 2c and 2d. Deep convective areas are initially distributed over three continental sectors: Africa, South America, and the Maritime Continent (Fig. 2e). After onset, the occurrence and intensity of penetrating clouds into the TTL show an increase, especially over equatorial Africa and South America. In addition, deep convection shows a more zonal organization along 12.5°N in the NH.

The vertical structure of cirrus frequency obtained from CALIOP is shown in Fig. 4 (color shading) for three convective sectors (from top to bottom): the Maritime Continent (110°E–130°E), Africa (10°E–40°E), and South America (280°E–310°E). Figures 4a and 4b (left and middle columns) show average values for periods A and B, and Fig. 4c (right column) shows the difference (B−A) with the 95% significant level of a Pearson’s Chi-square analysis. Also shown in Figs. 4a and 4b are mean cirrus cloud-top height (solid lines) and frequency of clouds at all altitudes (dotted lines) to know the center of convection.

Although there are characteristic differences among the three sectors, there is a common feature that the cirrus frequency increases at higher levels of the tropical SH and the equator, but decreases at the lower level of tropical NH in response to the equatorial stratospheric cooling. All grid points where the difference is statistically significant indicate the increase of the cirrus frequency in the TTL, except for ones in African sector below the TTL where the decrease occurs.

As indicated by the strong convection over the NH part of Maritime Continent sector and the frequent cirrus clouds widely observed in the vertical direction (Fig. 4b-top panels), the Asian monsoon is still very active in September 2007. Whereas over the SH part, the frequently-observed cirrus is found only in the upper part of TTL and strong convective activities are not seen in the lower atmosphere (Fig. 2f). After onset (period B), cirrus clouds in the TTL appear more frequently in the SH up to 20°S.

Over the African sector, cirrus clouds occur mainly over the convective region around the equator (Fig. 4-middle panels). The most prominent feature of the change in this sector is an increase in the cirrus cloud top height. Namely, after onset, cirrus clouds form at very high altitudes, even above 18 km. A significant decrease of the cirrus frequency observed below the TTL does not mean the decrease of the cirrus cloud formation, but clouds are formed at higher altitudes.

Over the South American sector, convective activity spreads over a wide latitudinal range around the equator, especially in the
SH reflecting more abundant water vapor at the lower troposphere. Cirrus clouds closely follow the distribution of convective activity (Fig. 4-bottom panels). The high cirrus cloud frequency region becomes higher (above 17 km) after onset, but the major change in this sector is the southward extension of cirrus with high statistical significance and convective clouds (Fig. 2f).

The formation of cirrus clouds associated with the SSW affects the water vapor budget in the TTL. Figures 2g and 2h display the water vapor volume mixing ratio at 100 hPa, as obtained from EOS MLS during periods A and B, respectively. The main dry region extends from the east coast of Africa to the western Pacific. Water vapor decreases by approximately 1 ppmv over the equatorial region (Fig. 3b), where the temperature decreases by about 1 K after onset (see Fig. 3a). The driest region is situated somewhat westward of the center of the coldest region (Fig. 2b).

Fig. 4. Latitude-pressure sections of cirrus cloud frequency [%] obtained from CALIOP for three convectively active sectors (from top to bottom rows): average over Maritime Continent sector (110°E−130°E), African sector (10°E−40°E), and South American sector (280°E−310°E). (a) and (b) show the averages for periods A and B, respectively, and (c) shows their difference (B−A). In (a) and (b), the solid lines indicate the average cirrus cloud top height as a function of latitude. Dotted lines indicate frequency [%] of clouds at all altitudes. Horizontal dashed line at 10 km indicates upper limit of cloud frequency. Horizontal dotted and dot-dashed lines located at 17 and 14 km are referred to as tropical tropopause height and lower level of TTL, respectively. The white color indicates no cirrus observation in (a) and (b) and/or less difference (5% or less) for (c). The box in (c) indicates the 95% significant level from a Pearson’s Chi-square test.

4. Summary and discussion

The present study assessed the co-variability of the stratosphere and troposphere in the tropics by analyzing changes in the meteorological and cloud fields (10-day means) before and after the onset of SSW. It is possible that other sources of tropospheric variation, such as Madden-Julian Oscillation (MJO), equatorial waves and cold surge, also contributed to these changes. However, during the analysis period, the global features of differences before and after onset of SSW are unrelated to these tropical phenomena (Figure not shown).

The present results can be summarized as follows. After the onset of SSW07 on 16 September, air temperature decreased within the equatorial stratosphere and TTL (Figs. 1b, 1d, 2a, 2b and 3a), leading to an increased frequency of cirrus clouds in the tropics (Figs. 1c, 2c and 2d). Although different regions show different characteristics, the onset of SSW was generally followed by an increase in cirrus cloud top height and the southward extension of cirrus clouds (Fig. 4). Differences were also observed among sectors. Over the Maritime Continent sector, the cirrus is frequently found only in the upper part of TTL at the SH, whereas cirrus clouds over the African and South American continents are accompanied by deep convective activity (Figs. 2 and 4). Over Africa, the change following onset is most apparent as an increase in the cloud top height, whereas over South America the change is most apparent as a southward shift of cirrus clouds and a region of deep convective activity.

The varying characteristics of the cloud response among different regions may be attributed to differences in water vapor transport (Figs. 2g and 2h). Analysis of the water vapor flux at...
100 hPa (Figures not shown) indicates that moist air moved from Southeast Asia to the colder equatorial region, transported by anticyclonic circulation associated with the Asian Monsoon. Once the moist air from the Asian Monsoon entered the tropical cold region, water vapor fluxes were rapidly attenuated due to the dehydration (cold trap), especially the downwind region in the equatorial SH. Although the general decrease of the water vapor is observed along the equator due to the equatorial cooling (Fig. 3b), it is interesting to note some increase of water vapor over Africa, where strong precipitation in the TTL is associated with the formation of the cirrus clouds (Figs. 2d and 2f). This suggests a cross-tropopause vertical transport of water vapor by deep convection (Chaboureau et al. 2007).

As mentioned above, the driest area in Fig. 2h is located westward of the lowest-temperature region (Fig. 2b). The water vapor transported by northeasterlies is likely to have been trapped by the coldest region, forming cirrus clouds, meaning that water vapor decreased downstream, west of the coldest region. In this region, the Maritime Continent the decrease in air temperature of the TTL associated with SSW resulted in enhanced condensation and the more formation of cirrus clouds in the TTL.

The observed characteristic changes in tropical clouds together with the occurrence of the SSW are: i) Frequent formation of higher-level cirrus clouds over the Maritime Continent where the horizontal transport of water vapor is important; ii) Intensified deep convective activity in the TTL over African continent where penetrating deep convective clouds are frequent; iii) Southward shift of convective clouds over South American continent where water vapor in the lower troposphere are abundant.

Frequent formation of cirrus clouds is easily understood as a direct response to the cooling in the TTL due to an increased B−D circulation associated with SSW event. Intensified deep convective activity may also be related with the increased B−D circulation as a numerical experiment performed by Thuburn and Craig (2000). Southward shift of the convective activity is consistent with a previous results of the study of the 2002 SSW (Eguchi and Kodera 2007), but it could be a coincidence. Further analysis is required to determine whether such an effect is real.

Southward shift of equatorial convective zone and cirrus clouds are observed in the case of the SSW event in September 2002 (Eguchi and Kodera 2007). September 2002 lies within the warm phase of the El Niño/Southern Oscillation (ENSO) cycle and equatorial convective activity exhibits more zonal structure along the equator, while September 2007 being a cold phase of ENSO, convective active regions are concentrated over the continents. Thus, less zonal feature of the cloud response to September 2007 SSW event may be attributed to a difference in the convective active regions due to ENSO cycle.

Regarding the question of how the stratosphere affects the troposphere, Collimore et al. (2003) formulated a working hypothesis that lower-stratospheric temperature influences the height of deep convection, and the deeper clouds with larger diameters lead to greater convergence of mass and moisture at low levels. Elsner and Jagger (2008) suggested that warming of the lower stratosphere results in decreased convective available potential energy and limits the intensity of tropical cyclones. These hypotheses are consistent with the present result that the stratospheric influence could be transmitted to the troposphere via a change in deep convection in the TTL, although the details of this process remain to be clarified in future studies.

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