Impact of the 2002 stratospheric warming in the southern hemisphere on the tropical cirrus clouds and convective activity

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1. Introduction

Recently, Kodera and Yamada [2004] have found that the tropical temperature became colder significantly during the stratospheric sudden warming in the southern hemisphere in September 2002 (Figure 1) [e.g., Krüger et al., 2005], and that the tropical convection became active and shifted toward the southern hemisphere (Figure 3) following the equatorial cooling due to the enhanced meridional circulation associated with the stratospheric warming (Figure 4).

Fig 1. Temperature at 50 hPa at south pole (red) and equator (green).
Fig 3. Latitudinal distribution of OLR deviation from September 19.
Fig 4. Mass stream function of the residual circulation derived from September 19, on September 21, 24, and 29.

Figures quoted from Kodera and Yamada [2004]
The aim of this study is to investigate the spatial and temporal variations of tropical cirrus clouds during one of the largest and well isolated stratospheric warming event in September 2002 in the southern hemisphere [e.g., Krüger et al., 2005], and to examine its influence on the cirrus clouds, convective clouds, and meteorological fields such as temperature.
3. Analysis data

• **MODIS Clouds Product daily data**: MODerate-resolution Imaging Spectroradiometer (MODIS) /Terra (MOD08_D3 Version 4.0)
  – September 1 - October 31, 2002
  – 1° × 1° grid
  – **Cirrus cloud fraction**
    • The cirrus cloud fraction is inferred from the cirrus bidirectional reflectance data retrieved from the 0.66 and 1.38 μm channels of the MODIS [Gao et al., 2002].

• **Meteorological variables**: National Centers for Environmental Prediction (NCEP) reanalysis 2 data
  – Temperature @ 50, 100 and 200 hPa

• **NOAA / OLR**
Retrieval process of cirrus clouds from MODIS/Terra

  - The apparent reflectance of the 1.38 μm band is essentially the bidirectional reflectance of cirrus clouds attenuated by the absorption of water vapor above cirrus clouds. The “virtual surface” (below the cirrus cloud layer) is located at 10 km in the tropics and 7 km in the middle and high latitudes.

Fig. 7. (a) 0.55-μm channel MODIS image obtained over Mongolia and the western part of China on 05:05-05:10 UTC, December 1, 2000. (b) 0.66-μm image that corresponds to the 0.55-μm channel image in (a). (c) 1.38-μm image corresponds to the images shown in (a) and (b). Note that the presence of cirrus clouds is evident from the 1.38-μm image, whereas these cirrus clouds are not clearly distinguishable from background in visible channel images.

Fig. 1. The solar and view geometry as well as atmosphere-earth configuration for the bidirectional reflectance of cirrus clouds from satellite observation.
4. Results: Stratospheric warming in autumn 2002

- The dates around September 19, 24, and 29 can be roughly classified as the pre-warming, mature and declining phases, respectively. The onset of the stratospheric warming occurs around September 21.

Fig 1. The latitude-time section of temperature at 50 hPa from September 1 to October 31, 2002. The contour interval is 4 K from 192 K to 220 K. The vertical dotted lines indicate September 19, 24 and 29.
• The temperature variation at 100 hPa is mainly confined within the convective region though the temperature at 50 hPa, in the lower stratosphere, varies more zonally.
Temperature variation @ 200 hPa

- On temperature at 200 hPa the western Pacific becomes warmer after the warming event possibly due to the latent heat released by the deep convection.
- The convection becomes to enhance during and after the mature phase, especially in the western Pacific.

Figure 2. (c) Same as (a) but for 200 hPa. The contour indicates OLR with the value of 170 [W/m²] (thick) and 200 [W/m²] (thin).

OLR with the values of 170 and 200 W/m² corresponds approximately to the outgoing radiation from 250 and 310 hPa, respectively.
• The cirrus clouds occur frequently over the Indian Ocean and the western and central Pacific during or starting from the mature phase.

• The enhanced convective activities over the Indian Ocean and western Pacific are observed from the mature phase or the end of the mature phase and lasts for about one weeks.

• Note that the high cirrus cloud fraction (>50%) is developed before the development of the deep convection (OLR < 170 [W/m²]) over the Indian Ocean and western Pacific.

Figure 3. Same as Figure 2 but for cirrus cloud fraction. The data is smoothed with a 15 point running mean (15 degrees). The contour indicates OLR with the value of 170 [W/m²] (thick) and 200 [W/m²] (thin).
Relationship between cirrus and convective clouds

Before the convection becomes active (i.e. the OLR decreases) around September 24, only some of the areas are found to have both cirrus cloud fraction of 50 % or above and OLR which is larger than 240 W/m².

After September 24, the OLR decreases and correlates better with cirrus cloud fraction as seen from the increased correlation coefficient. The correlation coefficients around September 24 and 27 are -0.75 and -0.86, respectively.

Figure 4. Scatter diagram of OLR and cirrus cloud fraction with averaged between 10S and 2.5N during September 18-20 (a), September 22-24 (b) and September 26-28 (c). The star marks indicate the average of cirrus cloud fraction and OLR. The numbers in right-bottom of each panel show correlation coefficient between OLR and cirrus cloud fraction. The vertical and horizontal dotted lines indicate the threshold of enhancing the convective activity and cirrus cloud fraction.
Time lag between generations of cirrus and convection (1)

The feature of the high cirrus occurrence, enhancing in the southern hemisphere, is consistent with the convective activity as shown in Kodera and Yamada [2004]; however, there is a time lag of several days between the generations of the convective clouds and the cirrus clouds in the southern hemisphere.

Figure 5. (a) Latitude-time section of zonal mean cirrus cloud fraction from September 1 to October 31, 2002. (b) Same as (a) but for OLR. The vertical dotted lines indicate September 19, 24 and 29.
The cirrus cloud fraction and convective activity are gradually enhanced after September 19. The cirrus cloud fraction reaches the maximum at about 35% on September 25, and the high cirrus fraction continues until October 4.

On the other hand, the convective activity reaches the maximum on October 4, after which the cirrus cloud fraction and convective activity decrease altogether.

Time lag between the generations of the cirrus and convective clouds in the southern hemisphere is especially noticeable over the Indian Ocean and western Pacific as shown in Figure 3.

**Figure 6.** Time series of cirrus cloud fraction (blue) and OLR (black) at equator smoothed with 5-day running mean. The vertical dotted lines indicate September 19, 24 and 29.
5. Summary

- The present study suggests that the tropical cirrus cloud variation is linked closely to the stratospheric warming event of the autumn 2002 in the southern hemisphere via the variations of the tropical upper tropospheric temperature and tropical convective activity associated with the stratospheric warming.

- The temperature variation in the upper troposphere and lower stratosphere is closely related to the stratospheric warming. After the onset of the stratospheric warming, the temperature at 50 hPa cools down zonally, while the temperature at 100 hPa becomes lower mainly over the convective areas, such as the Indian Ocean, the western Pacific and the South America.

- The cirrus cloud fraction in the tropics is enhanced during the mature and declining phases of the stratospheric warming, especially over the convective area at the south of the equator. There is a time lag of several days between the occurrences of cirrus clouds and deep convections in the tropics; the cirrus cloud fraction reached maximum several days before the minimum of the OLR on the tropical average fields is reached.
6. Schematic figure (Figure 7)

- (a) Pre-warming phase (around September 19): the active convection, cold area around the tropical tropopause and cirrus clouds exist at the north of the equator. The cold and high cirrus fraction areas are moving to the southern hemisphere.
(b) Mature phase (around September 24): Upward motion in the tropical stratosphere, especially in the south of the equator, is enhanced [See Figure 4 in Kodera and Yamada, 2004]. The convection appears in the southern hemisphere. The cirrus fraction reaches the highest.
(c) Declining phase (after September 29): The stratospheric upward motion decreases. On the other hand, the tropospheric upward motion and the convective activity increase. After the convective activity in the southern hemisphere reaches the maximum, the cirrus and convective clouds are diminished simultaneously.
7. Discussion

- Tropical tropopause region is cooled down by the enhanced upwelling due to stratospheric warming in the south polar region [Kodera and Yamada, 2004], forming the cirrus clouds in the uppermost troposphere and causing the upward motion around the tropical tropopause region due to the latent heat released by the formation of cirrus clouds, especially at the south of the equator.

- Hence the upwelling in the tropical stratosphere reaches the lower layer or more, and upward motion in the tropics becomes more intense (Figure 7 (a)) as shown in Figure 4 of Kodera and Yamada [2004].

- Through the latent heat released by the formation of cirrus clouds, the upper troposphere becomes less stable, and convection becomes more active, especially in the southern hemisphere (Figure 7 (b)). This enhanced convection creates stronger convergence of air and water vapor in the lower troposphere and organized convective system (figure 7 (c)).

- After the disappearance of the tropical upward motion in the stratosphere associated with the stratospheric warming, the cirrus clouds, which appear to be anvil cirrus, are accompanied by the deep convective system. This anvil cirrus keeps tropopause region cold for about one week after the stratospheric event.

- Once the convective activity becomes weak, the cirrus clouds disappear with declining convective activity, and the tropopause temperature increases gradually, as indicated by Hartman et al. [2001].
8. Future works

- Water vapor variation in the tropopause region during the stratospheric warming event
- Variation of cirrus altitude by using the lidar data (e.g., ICESat/GLAS, CALIPSO)
- Interannual variation of cirrus cloud associated with the stratospheric warming