NOTE AND CORRESPONDENCE

Sudden Changes in the Tropical Stratospheric and Tropospheric Circulation during January 2009

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Abstract

In mid-January 2009, sudden changes in circulation occurred in the tropical troposphere and stratosphere. Convective activity situated over the equatorial Maritime Continent showed an abrupt weakening, whereas that over the South American to African sectors became stronger. Changes also occurred in the latitudinal structure; convective activity in the Northern Hemisphere became weaker, whereas that in the Southern Hemisphere became stronger. The change in convective activity took place in association with a change in tropical circulation, from east–west to north–south type (i.e., from Walker- to Hadley-type circulation). Almost simultaneously with these events in the troposphere, a change in meridional circulation occurred in the stratosphere during a record-breaking stratospheric sudden warming event in January 2009. Stratospheric tropical temperature showed a decrease in response to a strengthening of the hemispherical meridional circulation. In the present study, we show how the stratospheric and tropospheric circulation changes are dynamically coupled.
Fig. 1. Longitude–time sections of the equatorial (a) OLR and (b) zonal wind at 150 hPa, averaged over 5°S–5°N from 1 January to 6 February 2009. Horizontal lines indicate 15 January 2009. The geographical distribution of the continents is shown in the bottom panels.

1. Introduction

The Hadley circulation is fundamentally a zonally symmetric north–south circulation. However, the geographical distribution of oceans and lands results in a zonally asymmetric structure (Dima and Wallace 2007), which creates east–west (Walker) circulation over the equator (Bjerknes 1969). Because the Hadley circulation is primarily driven by global-scale heating, temporal variation in the Hadley circulation is usually discussed at the interannual timescale i.e., as a response to sea surface temperatures (SST) or global warming (e.g., Oort and Yienger 1996; Tanaka et al. 2004; Mitas and Clement 2005).

Intraseasonal variations in the tropical convection usually occur at a regional scale, such as that related to propagation of the Madden–Julian Oscillation (MJO) or equatorial waves (e.g., Wheeler et al. 2000; Wheeler and Hendon 2004). The propagation of Rossby waves from the extratropics, as well as cold surges, also excites convection in the tropics, producing subseasonal variations in regional convective activity (Meehl et al. 1996). Accordingly, Hadley circulation related to short-term variations is generally a local meridional circulation or a “local Hadley circulation”.

In the present paper, we report an event that involved a large-scale change in tropical convection in response to a sudden change in circulation, from Walker- to Hadley-type circulation, in mid-January 2009. The abrupt change was not limited to the troposphere; the stratospheric mean meridional circulation changed at the same time due to a record breaking stratospheric sudden warming (SSW) event in January 2009 (Labitzke and Kunze 2009; Manney et al. 2009; Harada et al. 2010).

Kodera et al. (2006) showed that the tropical convection activity shifts southward following the NH SSW events. In this note, we show how a tropical tropospheric circulation change in mid-January 2009 is dynamically related to a stratospheric circulation.

2. Data

The principal meteorological dataset used in this study is the reanalysis dataset of the Japanese 25-year Reanalysis Project (JRA-25; Onogi et al. 2007) and its update by using the same Japan Meteorological Agency (JMA) Climate Data Assimilation System (JCDAS). The daily mean outgoing long-wave radiation (OLR) data are compiled by the National Oceanic and Atmospheric Administration (NOAA) (www.esrl.noaa.gov/psd/data). The low OLR indicates enhanced convection in the tropics. Cloud-top pressure data are from the cloud product of the moderate-resolution imaging spectroradiometer (MODIS) on board TERRA.
3. Results

3.1 Troposphere

Tropical convective activity during January 2009 is depicted in a longitude–time section of daily OLR over the equator (average, 5°S–5°N) (Fig. 1a). Low OLR region corresponds to a convectively active region. In early January, convective activity (blue region) is almost stationary and is located in the Western Pacific (around 115°E), although a slight eastward shift toward the western Pacific sector is recognized. A sudden change in equatorial convective activity occurs at around 15–16 January; convection becomes active from the South American to African sectors, while that around the Maritime Continent becomes weaker. The region of active convection propagates eastward from mid-January, from the Atlantic sector (30°W) across the Indian Ocean, reaching the Maritime Continent (110°E) in early February. During the same period, we observe a slower westward propagation of the region of active convection from the Atlantic sector (30°W) to the South American continent (70°W). Consequently, convection becomes globally active over the tropical band in late January to early February, except for over the Pacific Ocean east of the date line. Note that the early winter of 2008/2009 is a cold phase of the El Niño/Southern Oscillation (ENSO) cycle, meaning that the near surface condition over the equatorial central and eastern Pacific is unfavorable for convection.

East–west circulation (i.e., Walker circulation) is closely related to the distribution of regions of active convection over the equator. In order to emphasize a global feature, we analyze the zonal winds at 150 hPa; a longitude–time section is shown in Fig. 1b. A clear zonal wavenumber 1 structure is seen in the zonal wind field during early January. Westerlies and easterlies cover the western and eastern hemispheres, respectively. The westerlies show a sudden weakening after 15 January, and easterlies appear over South America and Africa following the enhancement of convective activity in these regions. Consequently, the wavenumber 1 pattern disappears and a wavenumber 3 or 4 pattern appears, corresponding to the distribution of the continents.

The changes observed in mid-January 2009 are not limited to the equatorial region. Figure 2a shows the velocity potential function at 200 hPa averaged over the 7-day periods before 15 January (left-hand) and after 15 January (right-hand). Before 15 January, the spatial structure of the velocity potential shows a clear zonal
wavenumber 1 structure, consistent with the zonal wind pattern in Fig. 1b. A large-scale divergence center is located over the Maritime Continent, and the convergent region extends from the African to South American continents. After 15 January, more zonal structure and a north–south seesaw manifest. Specifically divergent centers appear in the Southern Hemisphere (SH) over the African and South American continents, in addition to the Australian continent. A convergent center is newly formed over the subtropical North Pacific. The zonal symmetric and asymmetric components of 200 hPa velocity potential are used as indices of Hadley- and Walker-type circulation, respectively (Tanaka et al. 2004). Accordingly, the change in tropical circulation that occurred in mid-January can be characterized as a change from Walker- to Hadley-type circulation.

Rapid change in the velocity potential should be a reflection of the redistribution of large-scale divergence due to deep convection. Cloud top pressure observed by MODIS/TERRA, averaged for 7-day similar to those in Fig. 2a, is displayed in the Fig. 2b. Prior to 15 January, high clouds are mainly seen around the Maritime Continent and the South Pacific convergence zone (SPCZ), which is a common feature of the cold phase of ENSO (Ropelewski and Halpert 1989). High clouds around the Maritime Continent show a marked decrease after 15 January. During this period, high clouds form over the continents in the SH at latitudes of 15°S–20°S. The negative centers of velocity potential are coincident with the regions of high top clouds. Over the African sector, distribution of high top clouds shows relatively small difference between the two periods. Note, however, that two small regions of high top clouds near Madagascar during the period of 16–22 January are those related to tropical cyclone Fanele and tropical storm Eric. They are small in horizontal scale but the vertical flows are quite important. This creates a strong divergence center over Africa in Fig. 2a– right.

As discussed in the Introduction, tropical circulation is influenced by cold surges and Rossby waves from the extratropics. Here, we briefly overview these influences as they occurred in mid-January 2009. A cold surge from China occurred from 9 to 14 January, when convective activity over the equatorial Western Pacific showed an increase. These changes are evident as a slight eastward shift and extension of the region of convective activity shown in Fig. 1a. However, this does not explain the increase in convective activity over the South America–Africa sector.

A record-breaking SSW in January 2009 was initiated by the amplification of a ridge over the west coast of the North American continent (Harada et al. 2010). Propagation of a quasi-stationary Rossby wave packet in the upper troposphere from North America to the Arabian Peninsula, across the North Atlantic and North Africa, is observed at around 16–22 January (see Fig. 8 in Harada et al. 2010). The impact of this upper tropospheric Rossby wave on tropical convection can be seen over North Africa and the Arabian Peninsula; however, the change over the equator and farther south in the SH cannot be attributed to this wave activity.

An important component of equatorial intraseasonal variation in convective activity is the MJO, which is characterized by the eastward propagation of a region of active convection and zonal winds. Monitoring of the modes of coherent tropical variability, as undertaken by the Bureau of Meteorology Research Centre (http://cawcr.gov.au/bmrc/clfor/cfstaff/maw/mmaproom/OLR_modes/index.htm), indicates that following the change on 15 January, the convective activity coupled with equatorial Kelvin and Rossby waves was excited almost simultaneously over the Atlantic and Pacific oceans, adding to an MJO-like variation over the Indian Ocean at around 20 January. However, the abrupt change to a more zonal structure at around 15 January is difficult to explain in terms of propagation of the MJO.

The above observations indicate that the large-scale change in the equatorial convective activity that occurred around 15 January 2009, is not easily explained solely in terms of tropospheric variability. A previous statistical study of the influence of the Arctic SSW on the tropical troposphere reported a southward shift of the convection following the SSW (Kodera 2006). In the following subsection, we will study the stratospheric variation in connection to the troposphere.

3.2 Stratosphere

A feature of the stratospheric circulation during a winter from December 2008 to February 2009 is depicted in Fig. 3. North polar temperature at 10 hPa rapidly increases from around 19 January and attains a peak value on 23 January (Fig. 3a). Tropical lower stratospheric temperature (at 50 hPa) decreases from 13 January until 9 February.

Figure 3b shows the eddy heat flux at 100 hPa, averaged over 45°N–75°N. The eddy heat flux is proportional to the vertical component of the quasi-geostrophic Eliassen–Palm flux (Andrews et al. 1987), and is an indicator of the vertical propagation of planetary waves. Enhanced stratospheric planetary wave activity induces a hemispherical meridional circulation (Garcia 1987; Randel 1993). Simultaneous increase of the upwelling in the tropical stratosphere at 50 hPa with
the eddy heat flux is clearly seen in Fig. 3c (upwelling is negative in pressure coordinate vertical velocity, $\omega$). Decrease of the tropical temperature starts following the increase of the upwelling. However, the warming of polar temperature is delayed about a week relative to the decrease in tropical temperatures. This happens because the planetary waves propagate equatorward before becoming focused over high latitudes. Downwelling tends to occur first at the edge of polar vortex and shift poleward.

In the stratosphere, intensification of upwelling occurs in a wide range of the tropics. In the troposphere, the change is more prominent in the meridional structure of the upwelling. Figure 3d shows latitude–time sections of the zonal-mean pressure coordinate vertical velocity at 200 hPa. An upward branch in the NH located around $5^\circ$N–$10^\circ$N shifts suddenly southward over the equator in the period of 15–20 January. A southward shift is also seen for the SH upwelling zone situated around $15^\circ$S (this feature will be clearly seen in Fig. 4b). In a previous study (Fig. 4 of Eguchi and Kodera 2007), it was shown that a sudden transition of the meridional circulation in the tropical troposphere can occur through feedback with the water vapor transport and convective activity. Figure 3e shows latitude–time sections of anomalous specific humidity at 850 hPa. Southward shift of upwelling zone in Fig. 3d is accompanied by a sudden increase of the lower tropospheric water vapor around 15 January in the tropical SH and the equator.

The residual mean circulation, according to the Transformed Eulerian Mean framework (e.g., Andrews et al. 1987), allows for a detailed study of the relationship between tropospheric and stratospheric circulation. Figure 4 shows consecutive 3-day mean mass stream functions of the residual circulation. To illustrate the evolution during the SSW event, the mass stream functions are shown as the departure from the 3-day mean for 11–13 January—the period of the initiation of the vertical propagation of planetary waves (see Fig. 3b).

Initially (14–16 January), the change in stratospheric circulation occurs as enhanced upwelling in the tropics and downwelling around $50^\circ$N, outside of the polar vortex. No clear structure is found in the troposphere, except for a circulation around $60^\circ$N induced by amplified waves prior to propagation into the stratosphere. In the following days (17–19 January), strong downwelling appears in the NH polar region and stratospheric warming begins. Correspondingly, upwelling is enhanced in the tropics of the stratosphere at around $10^\circ$S–$20^\circ$S and $10^\circ$N–$20^\circ$N. Upwelling in the troposphere develops at around two latitudes ($20^\circ$S and the equator), accompanied by downwelling at the north side. This corresponds

Fig. 3. Time series of (a) the North polar temperature at 10 hPa (red line) and tropical (20°S–20°N) temperature at 50 hPa (black line), (b) eddy heat flux at 100 hPa averaged over 45°N–75°N, and (c) zonally averaged tropical (20°S–20°N) pressure coordinate vertical velocity at 50 hPa. Latitude–time sections of (d) zonal mean pressure coordinate vertical velocity at 200 hPa and (e) anomalous specific humidity at 850 hPa. Anomalies are defined as departure from climatology and winter mean. Period of analysis is from 1 December 2008 to 28 February 2009. Vertical lines indicate 15 January.
to a southward shift of the two upwelling zones shown in Fig. 3d. Stream functions are generally positive at upper levels but negative at lower levels between latitudes of 15°S and 60°N. Circulation around positive and negative peaks corresponds to clockwise and counterclockwise circulations, respectively. This means that the southward flow develops in the upper troposphere, in connection with enhanced northward circulation in the stratosphere.

An increase of the meridional circulation in the lower stratosphere between 20°N and 40°N is also noted during this period (17–19 January). However, this smaller-scale meridional circulation between the subtropics and mid-latitudes of the NH soon diminishes during the following period (20–22 January), which is marked by enhanced hemispherical meridional circulation. During 20–22 January, tropospheric upwellings merge together near the equator and the tropical tropospheric circulation becomes a more simple structure. During 23–25 January, stratospheric upwelling mainly occurs around the equatorial NH. This period sees ongoing development of the equatorial tropospheric cell related to equatorial upwelling.

4. Summary and Discussion

A pronounced change in the tropical circulation occurred globally in mid-January 2009. Convective activity centered over the equatorial Maritime Continent showed a rapid decrease and convection became active over the tropical SH continents. This change in tropospheric circulation may be characterized as a change from Walker- to Hadley-type circulation. At the same time, tropical stratospheric temperature showed a decrease in response to increased hemispherical meridional circulation due to enhanced planetary wave activity. Increase of the convective activity in the equatorial SH following the SSW in January 2009 is consistent with the previous statistical study of the impact of NH SSW (Kodera 2006).

The connection of the stratospheric circulation with the troposphere is well depicted by the evolution of the residual mean meridional circulation, as shown in Fig. 4. The southward shift in upwelling that appears at 200 hPa around 15 January (see Fig. 3d) could be understood as a response to enhanced stratospheric meridional circulation extending to the SH. The essential feature of the stratospheric variation associated with the SSW is strengthening of the hemispherical meridional circulation. We also note that positive and negative stream functions are more or less randomly distributed in the troposphere during the early stages (14–16 January). Once the stratospheric hemispherical meridional circulation intensified, however, the functions formed a more organized structure. Positive values tend to be found from the upper troposphere to the lower stratosphere, while negative values are more commonly found in the middle and lower troposphere, especially at lati-
tudes between 15°S and 60°N. This configuration indicates increased southward flow in the upper troposphere, which may constitute a lower branch of the intensified hemispherical meridional circulation.

Another noticeable change in the troposphere is enhanced equatorial upwelling during the later period. The development of vertical velocity occurred as an upwelling–downwelling pair around the equator from 17–19 to 23–25 January. This seesaw is not directly related to the stratospheric circulation. It occurs because of a tropospheric feedback process involving convergence of water vapor in the lower troposphere (Fig. 3e) as discussed before.

Although a relationship is suggested between the stratospheric and tropospheric circulations, the causal relationship is difficult to determine solely from observational data. Therefore, to gain an insight into the influence on the troposphere of stratospheric meridional circulation, we compare the present result with that of a numerical experiment performed by Yukimoto and Kodera (2007). In their experiment, the influence of stratospheric circulation was studied by adding angular momentum to the winter stratosphere in a Meteorological Research Institute (MRI) coupled ocean general circulation model (MRI-CGCM2.3) (Yukimoto et al. 2006). The eastward and westward momentum forcing are essentially the same as those used by Thuburn and Craig (2000), but they are applied only in the winter stratosphere. In Yukimoto and Kodera (2007) only an eastward forcing (stronger polar night jet) case is illustrated, although a westward forcing case (weaker polar night jet) had also been performed. Differences between the modeled stronger and weaker polar jet cases can be used as a proxy for the differences in circulation before and after the observed SSW event, although the time scale of the experiment is longer. Figure 5 shows the difference in the January mean meridional circulation between the westward and eastward momentum forcing experiments, each integrated for 100 years. The deceleration of stratospheric zonal wind induces upward motion in the equatorial stratosphere and sinking motion in the Arctic. The upward motion of the equatorial stratosphere extends to the lower level and is connected with equatorial upwelling in the troposphere. A positive cell of the stream function is located in the troposphere, immediately north of the equator, sandwiched between two negative cells. This pattern is similar to those shown in Fig. 4c and 4d for a period of relatively strong stratospheric meridional circulation, thereby supporting the interpretation that the change in tropospheric tropical circulation in mid-January 2009 occurred in connection with a change in stratospheric meridional circulation.

In the present study, we made use of JMA reanalysis data. To assess the reliability of the result regarding anomalous meridional circulation (Fig. 4), the same analysis was performed using European Center for Medium range Weather Forecasting (ECMWF) Interim Reanalysis data. At the time when the stratospheric meridional circulation becomes strong (23–25 January), both sets of reanalysis data give more or less similar results. However, during the early stages, when the stratospheric hemispherical meridional circulation is weak (14–16 January), a large difference is found in the stratosphere. In the ECMWF result, smaller-scale patterns are dominant in the stratosphere, whereas a hemispherical circulation pattern has already emerged in the JMA result (Fig. 4a). It is possible that the ECMWF stratospheric analysis includes more small-scale variations due to gravity waves, which appear to be filtered in the JMA stratospheric analysis. This filtering-out may facilitate finding small amplitude hemispheric-scale stratospheric variability.

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References


