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Observational evidence of deep convection over Indonesian sector in relation with major stratospheric warming events of 2003–04 and 2005–06

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ABSTRACT

The major sudden stratospheric warming (SSW) events of 2003–04 and 2005–06 are considered to investigate changes in equatorial convection due to circulation changes associated with the SSW events. It is observed that the SSW events are accompanied by a considerable decrease in Outgoing Longwave Radiation (OLR), a proxy for tropical convection, over equatorial latitudes (15°N–15°S) in the Indonesian sector (90°E–150°E). However, unlike noted by earlier observations, the zonal mean OLR does not show any notable relationship with the SSW events. It can be explained from the latitude–longitude map of potential vorticity (PV) at 100 hPa, which shows a tongue of high PV emanating from high latitudes towards equator and converges in the longitude band of 90°E–150°E on the day of peak warming at 1 hPa in the case of 2003–04 and 10 hPa in the case of 2005–06. The latitude-height map of Eliassen–Palm (EP) vector and its divergence show convergence of EP flux in the upper troposphere at latitudes even lower than 20°N on these days. Further, vertical winds computed from the convergence of momentum flux are upward indicating convective activity at low-latitudes and downward at mid-latitudes.

1. Introduction

Sudden stratospheric warming (SSW) is a dramatic event in the winter polar middle atmosphere, which involves profound changes of temperature, wind and circulation region within a short span of time. The widely accepted mechanism for the formation of warming event proposed by Matsuno (1971) is the rapid growth of vertically propagating planetary waves from troposphere to stratosphere and their interaction with the background flow. The rapidly varying planetary wave Eliassen–Palm (EP) flux divergence induces clockwise circulation in the northern hemispheric stratosphere and anti-clockwise circulation in the mesosphere (Garcia, 1987). The adiabatic effects associated with the stratospheric cell produce strong warming in the high-latitude winter stratosphere and smaller cooling in the tropics.

The 'downward control' principle of Haynes et al. (1991) suggests that the convergence or divergence of the meridional flow induces vertical flow below. Though it is expected that there cannot be significant effect of stratosphere on troposphere, as the air density of the stratosphere is much lower than that of the troposphere, the idealized general circulation model experiment of Thuburn and Craig (2000) demonstrated that the stratospheric meridional circulation change can affect the adiabatic heating rate of convection in the equatorial troposphere, as its influence could extend down at least as far as the main convective outflow level near 12–13 km, some 5 km below the tropopause.

Kodera and Yamada (2004) observed that a major warming, in which case, the eastward winter circulation gets decelerated and replaced by westward winds, of the southern hemisphere in September 2002 produced a north–south seesaw of tropical convection activity. Kodera (2006) also noted similar features resulting from the composite analysis of twelve major warming events occurred at high latitude northern hemisphere. Eguchi and Kodera (2007) suggested that the enhanced wave forcing in the tropical stratosphere induced upwelling, which is further extended in the equatorial troposphere leading to deep convection through increased mass and water vapor convergence in the lower levels.

In the present work, the major sudden stratospheric warming (SSW) events occurred during the years 2003–04 and 2005–06 are considered to investigate changes in convective activity over equatorial region. It is important to look into the behavior of background variables, namely, quasi-biennial oscillation (QBO) and El-Nino during these winters, as both can influence the occurrence of SSW events. If the QBO is in its westward phase, the atmospheric waveguide is modified in such a way that upward-propagating Rossby waves are focused on the polar vortex, intensifying their interaction with the mean flow. It is found that the QBO winds are in transition phase from westward to eastward during these winters. Experiments with Whole

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Atmosphere Community Climate Model (WACCM) under perpetual January conditions indicate that SSWs are twice as likely to occur in El Niño winters as in La Niña winters (Taguchi and Hartmann, 2006). However, both 2003–04 and 2005–06 winters are not preceded by strong El-Nino events and the occurrence of SSW events is not influenced by the equatorial processes.

To identify the SSW events, the UKMO (UK Met Office) data are used. The UKMO dataset is a result of assimilation of in situ and remotely sensed data into a numerical forecast model of the stratosphere and troposphere (Swinbank and O'Neill, 1994). The output of the assimilation is global fields of daily temperatures, geopotential heights, and wind components at pressure levels from the surface up to 0.1 hPa. The generated data fields have global coverage with 2.5° and 3.75° steps in latitude and longitude, respectively. The UKMO data well represent the global features of stratospheric thermodynamics and have frequently been used to study different dynamical events in the stratosphere including SSW events (Dowdy et al., 2004; Cho et al., 2004). Besides, interpolated outgoing long-wave radiation (OLR) data used in the present study are obtained from the Climate Diagnostic Center (CDC) of NOAA. This parameter is used as an indicator of deep convection in the tropical region (Liebmann and Hartmann, 1982).

2. Results

Fig. 1(a) and (b) shows the state of winter hemisphere at 10 hPa, 1 hPa and 0.3 hPa for 1–120 days starting from 01 November 2003. The SSW event is identified from the positive poleward temperature difference at 10 hPa during day numbers 49–69 (19 December 2003–14 January 2004) with a maximum temperature difference of 27 K occurred on day number 58 (Fig. 1a). This is a major warming event, as winds decelerate after day number 40 from 48 m/s, reverses to westward and attains maximum of 38 m/s on day number 53 (Fig. 1b). The westward winds again turn to eastward for about a week and it again changes to westward reaching a maximum of 20 m/s on day number 66. Though the event is identified at 10 hPa as per WMO definition (Quiroz, 1979), the warming events occur earlier at 1 hPa and 0.3 hPa around day number 42. It may be noted that the maximum temperature difference of 40 K is observed at 1 hPa on day number 46, whereas it is only 27 K at 10 hPa. Manney et al. (2005) summarized the most prominent characteristics of the 2003–2004 northern hemisphere winters. Their results showed that this warming event was characterized by an extraordinary long vortex disruption in the lower and middle stratosphere, with strong and rapid recovery of the vortex in the upper stratosphere. As discussed earlier, the meridional circulation associated with any warming event is expected to induce upwelling in the equatorial region. As OLR has been used as a proxy for tropical convection, the time variations of zonal mean OLR averaged for equatorial northern hemisphere (ENH) (5°N–15°N), equator (EQ) (5°S–5°N) and equatorial southern hemisphere (ESH) (5°S–15°S) are compared with those of poleward temperature difference. It is observed that the zonal mean OLR (Fig. 1c) does not show any notable relationship with the SSW event and they just show an increasing tendency over ENH and decreasing tendency over equator and ESH.

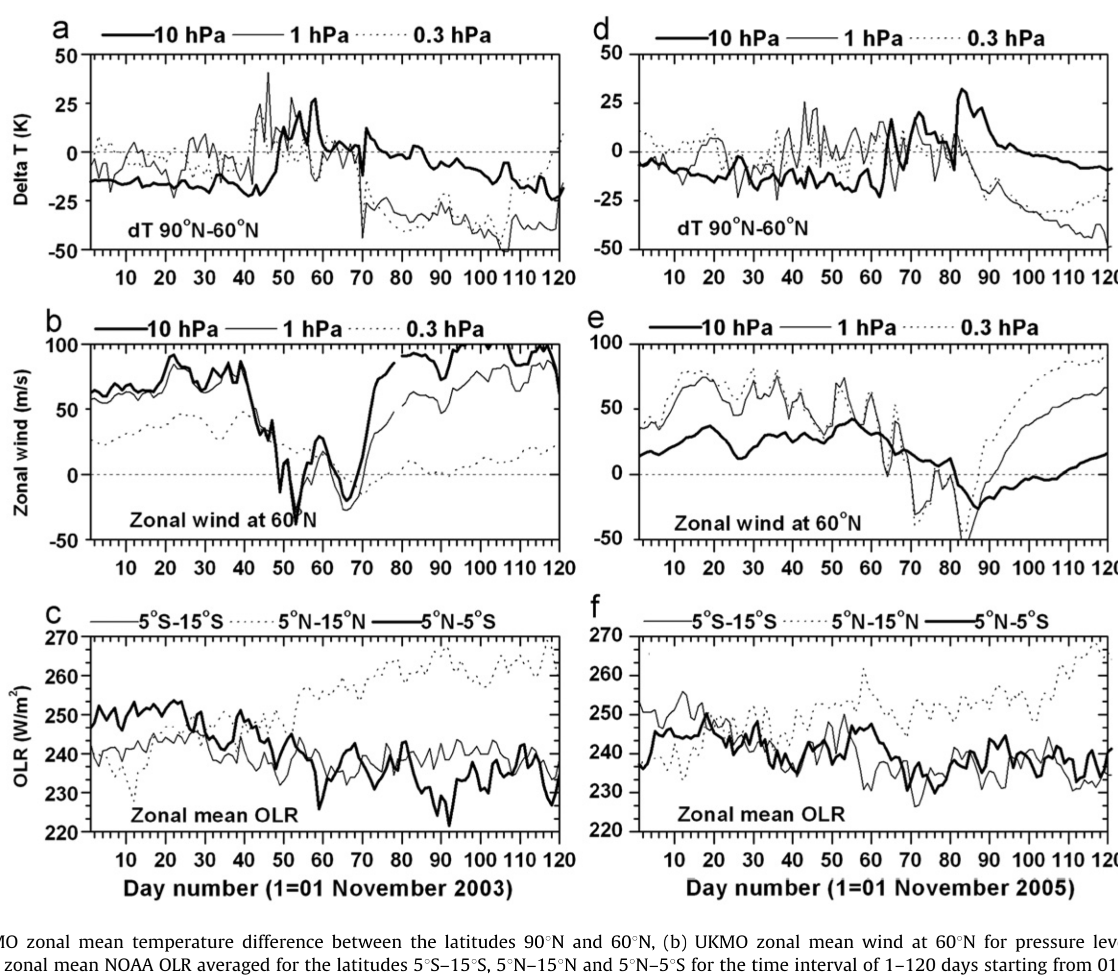

Fig. 1. (a) UKMO zonal mean temperature difference between the latitudes 90°N and 60°N, (b) UKMO zonal mean wind at 60°N for pressure levels 10 hPa, 1 hPa and 0.3 hPa, (c) zonal mean NOAA OLR averaged for the latitudes 5°S–15°S, 5°N–15°N and 5°N–5°S for the time interval of 1–120 days starting from 01 November 2003. (d–f) Same as (a–c) except that it is for the time interval of 1–120 days starting from 01 November 2005.

Fig. 1d–e shows the same as Fig. 1a–b, except that it is for the time interval of 1–120 days from 01 November 2005. In this case, the temperature difference between the latitudes 90°N and 60°N shows that there are a series of warming anomalies, which can be inferred from the positive temperature difference at 10 hPa on day numbers 64–66, 69–80 and 82–98 (Fig. 1d). The maximum temperature differences of 16 K, 20 K and 32 K are observed on day numbers 65, 72 and 83 during the three warming cases, respectively. Though there are three successive warming events, only the third event is the major warming event, as it is accompanied by the reversal of zonal winds from eastward to westward (Fig. 1e). The zonal mean wind at 60°N starts decelerating after day number 55 (25 December 2005) itself, reverses its direction to westward on day number 82 (21 January 2006), attains maximum westward wind of 26 m/s on day number 87 (26 January 2006) and reverses again to eastward direction on day number 109 (17 February 2006). Larger warming is noticed in this case at 10 hPa than at 1 hPa and 0.3 hPa. The 2006 SSW event is a remarkable event with extended period of nearly one month of polar vortex disruption and zonal wind reversal observed in the lower and middle stratosphere (Manney et al., 2008). It is a polar vortex displacement event, whereas the one of 2009 is the polar vortex split event (Manney et al., 2009). In the case of 2005–06 also, the daily zonal mean OLR shows a decreasing trend over equator and ESH whereas it shows an increasing trend over ENH (Fig. 1f).

For both 2003–04 and 2005–06 cases, the time variation of poleward temperature difference is compared with the longitude-time cross section of OLR averaged for the latitudes 15°S–15°N and found that lower OLR is observed in the longitude band 90°–150°E and 200°–250°E in relation with the SSW event (Fig. 2a). In other longitudes, no notable relationship exists between OLR and stratospheric poleward temperature difference. In the case of 2003–04, the equatorial OLR averaged for 90°–150°E shows large convective activity (<200 W/m^2 OLR) during day numbers 40–53 with the lowest OLR value of 169 W/m^2 on day number 50 (Fig. 2b). It may be recalled that though peak warming day occurred at 10 hPa on day number 58, the onset of warming started much earlier at higher heights (1 hPa) on day number 43 and the peak warming (40 K) is observed on day number 46 (Fig. 1a). The OLR averaged for 200°–250°E shows lower values over ENH on day number 39, a few days prior to the lower OLR at EQ over Indonesian sector (Fig. 2c).

In the case of 2005–06, the OLR averaged for the longitude band 90°E–150°E (Indonesian sector) shows large convective activity ($\sim$170 W/m^2) over ESH (Fig. 2e) during the time of positive poleward temperature difference at 10 hPa. The OLR value of 170 W/m^2 is observed on day number 81 over ESH. This is the lowest OLR value of entire observation period shown in the figure. The large convective activity is also noted over EQ with OLR value of 185 W/m^2 on day number 77. The ENH OLR shows relatively less convective activity. The convective activity over EQ, ENH and ESH decreases drastically after the warming event. In this case also, less values of OLR averaged for 200°–250°E are observed on day numbers 72 and 85 over ENH (Fig. 2f).

The relation between the SSW and the deep tropical convection comes through planetary (Rossby) waves. The Rossby waves

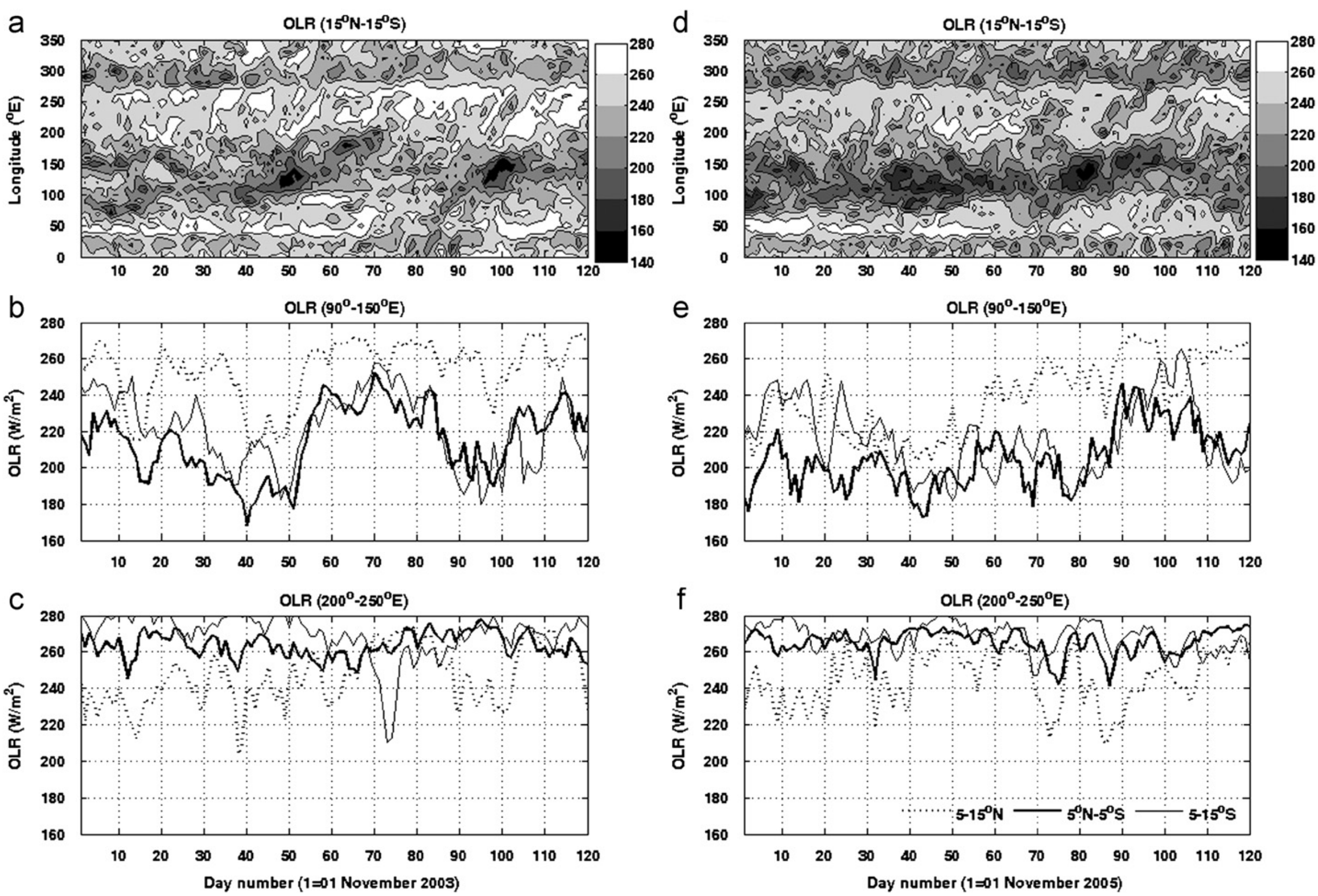

Fig. 2. (a) Longitude-time variation of OLR averaged for the latitudes 15°S–15°N, (b) 90°–150°E mean OLR averaged for the latitudes 5°S–15°S, 5°N–15°N, 5°N–5°S, (c) 200°–250°E mean OLR averaged for the latitudes 5°S–15°S, 5°N–15°N, 5°N–5°S for the time interval 1–120 days starting from 01 November 2003. (d–f) Same as (a–c) but for the time interval 1–120 days starting from 01 November 2005.

that propagate into the polar vortex can, sometimes, break due to their large amplitudes and the wave breaking produces intrusions of stratospheric air with high potential vorticity (PV) into the tropical upper troposphere (Waugh and Polvani, 2000). Dunkerton and Delisi (1986) suggested that the temporal evolution of the size, shape and orientation of the main circumpolar vortex can be revealed by potential vorticty field and the size of the vortex determines the range of latitudes over which planetary waves were able to propagate. Waugh and Funatsu (2003) indicated a close relationship between these PV intrusions and deep convection at the downstream side of the intrusions. To understand the increase of convective activity only over Indonesian region, latitude–longitude maps of ERA-interim potential vorticity (PV) at 100 hPa for different days are shown in Figs. 3 and 4 for the day numbers 46–52 and 75–81, respectively, for the years 2003–04 and 2005–06. From the figures, we can infer that in the case of 2003–04 (Fig. 3a–g), two tongues of high-PV emanating from northern polar latitudes extending further equatorward in the longitude bands west of 100°E and east of 200°E. As they approach low latitudes, the former turns westward and the latter turns eastward and both converge in the longitude region 90°E–150°E close to equator. This feature is more evident on day numbers 47–50 during the winter 2003–04. In the equatorial southern hemisphere also, there is a PV intrusion, however with less magnitude, in the longitude bands (100°E–150°E) on day numbers 47, 51, 52 and 53 in particular. Waugh and Polvani (2000) also noted the simultaneous occurrence of northern and southern intrusions. They observed that for every third northern intrusion event, there is also a southern event in the same region. In the present study, the zonal wind at 100 hPa shown in Fig. 3h shows presence of strong eastward winds in the longitude bands 90–220°E, 0–50°E and 250–300°E. Weaker eastward winds are present in the longitudes 50–100°E and 220–250°E. It is in these weaker eastward winds, PV advection from high latitude to low-latitude occurs. In the case of 2005–06 (Fig. 4a–g), the PV intrusion east of 100°E is not so significant. However, PV intrusion occurs east of 200°E as a narrow tongue extending even to equator. As it approaches equatorial latitudes, it also turns towards westward. This feature is more evident on day numbers 74 and 77. In the equatorial southern hemisphere also, PV intrusion is observed in the longitude bands 100°E–150°E on day numbers 78–80. Strong eastward winds are observed continuously in the longitude band 0–210°E and a limited longitude region around 250°E (Fig. 4h). Weaker eastward winds are present in the longitude region 210–240°E. PV advection occurs in this narrow longitude region of weaker eastward winds. It may be recalled that the low OLR is observed over the longitudes 90°E–150°E on 77 at EQ. The PV maps give evidence of intrusion of air mass from high-latitudes to limited longitude band. The PV advection is associated with

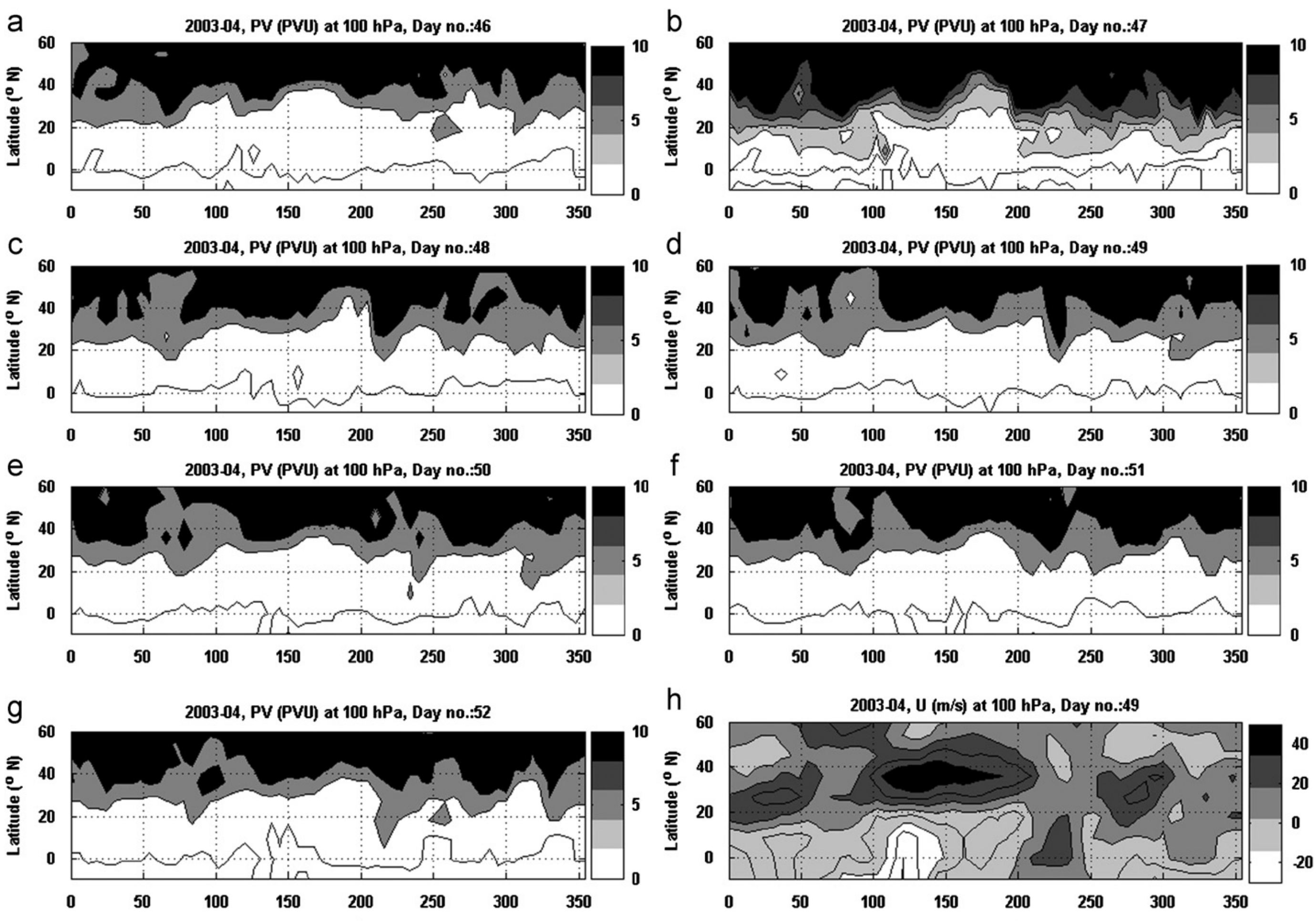

Fig. 3. (a–g) Latitude–longitude map of potential vorticity ($Km^2kg^{-1}s^{-1}$) at 100 hPa for the day numbers from 46 to 52 for the year 2003–04 (Day number 01 is 01 November of 2003), (h) Latitude–longitude map of zonal wind (m/s) at 100 hPa for the day number 49.

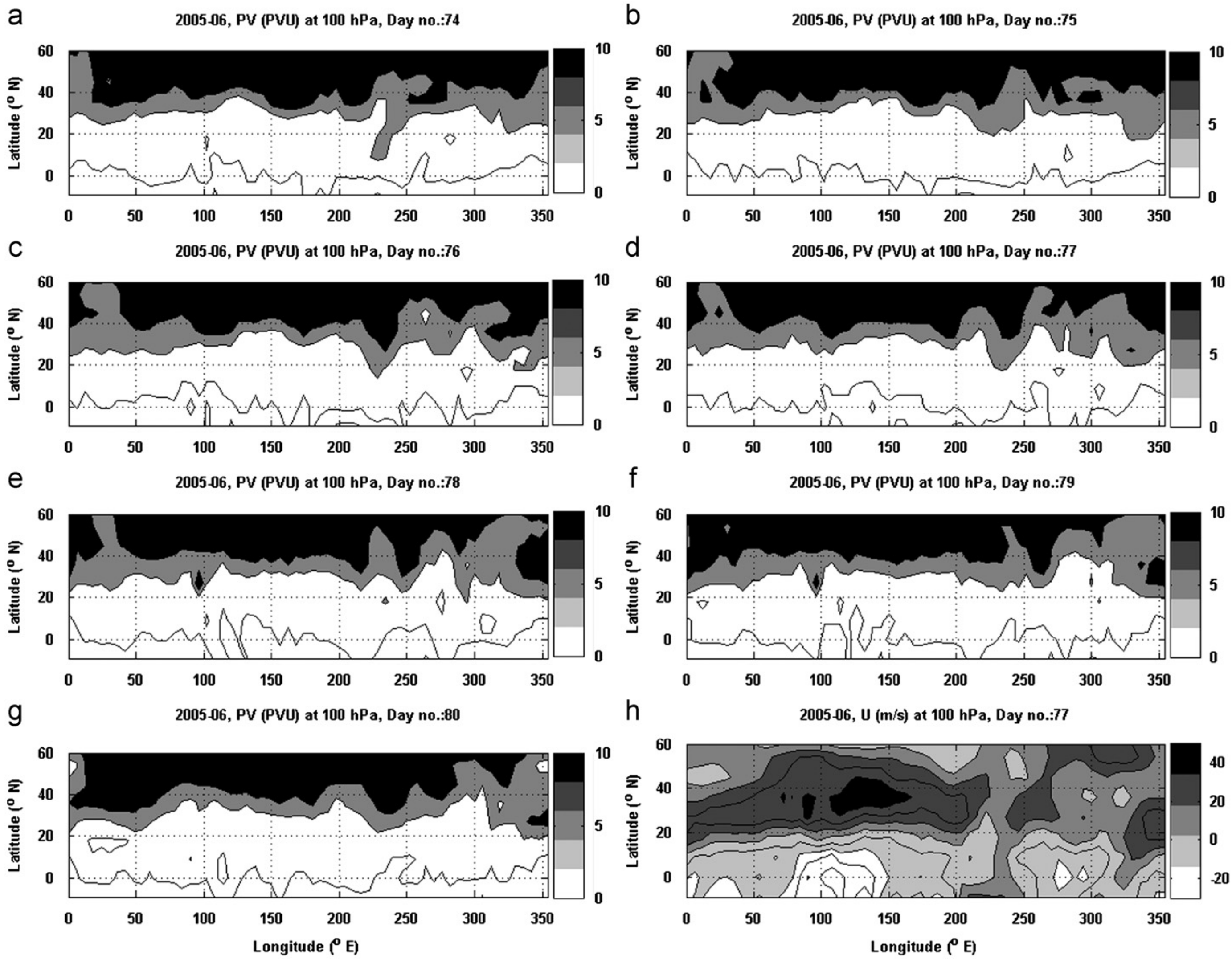

Fig. 4. (a–g) Same as Fig. 3 but for the day numbers 75–82 for the year 2005–06 (Day number 01 is 01 November 2005). (h) Latitude–longitude map of zonal wind (m/s) at 100 hPa for the day number 77.

decreased static stability within and below and hence it could be the reason for the decrease of OLR observed only over limited longitude region (Indonesian sector) and not in zonal mean.

The large convective activity occurs, when maximum temperature difference is observed at 1 hPa in the case of 2003–04 and 10 hPa in the case of 2005–06. It may be noted that the temperature difference is larger at 1 hPa than at 10 hPa. In order to understand the difference in the response between the two SSW events, the Eliassen–Palm (EP) flux vector and its divergence (Andrews et al., 1987), estimated using ERA-interim pressure, temperature, zonal and meridional wind values are shown in Figs. 5a and 5b, respectively, for 2003–04 and 2005–06 for several consecutive days. The orientation of the EP flux vector indicates the propagation direction of the planetary waves (Kanzawa, 1982). In general, EP vectors point towards low-latitudes in the upper troposphere at latitudes 30°N equatorward and the vectors point towards poleward in the lower troposphere (below ~400 hPa) at latitudes 40°N poleward. These observations clearly suggest that the planetary waves are generated in the latitude region 30°N–40°N due to topography or land–sea thermal contrast. For the 2003–04 case, the EP vectors are confined to 20°N poleward, on the day of peak warming at 10 hPa (day number 58), whereas they extend further towards equator on the day numbers 45–46 and 52, when the poleward temperature difference at 1 hPa is larger than at 10 hPa. The divergence of EP flux is negative indicating convergence EP flux. In the case of 2005–06, the EP vectors reach lower latitudes around the days of peak warming at 10 hPa, whereas they are limited to subtropics around the days of peak warming at 1 hPa. From the figure, we can infer that the planetary waves propagate towards equator in the upper troposphere region and there is a convergence of wave flux. As vorticity is proportional to Laplacian of geopotential, increasing vorticity means falling geopotential and vertical motion field can be determined uniquely by the geopotential (Holton, 2004). Haynes et al. (1991) formulated the "downward control principle" showing that the mean vertical velocity on a given pressure level is approximately proportional to the meridional gradient of the vertically integrated zonal force per unit mass exerted by the waves above that level. We estimate the zonal mean vertical velocity as a function of latitude and altitude (pressure level) using the following procedure, considering convergence of planetary wave momentum flux alone, to see whether it is positive (upward) at equatorial and low latitudes or not. In the steady state, the region of momentum flux convergence in the upper troposphere is balanced by mean equatorial flow. The momentum budget, in the free atmosphere, is given by, $-f\overline{v} = (1/\rho)(\partial/\partial y)$

($\overline{u'v'}$). Applying continuity, this flow becomes vertical motion at the edges of the region. Integrating the continuity equation, given by $\partial\overline{v}/\partial y = -(1/\rho)(\partial/\partial z)(\rho\overline{w})$, zonal mean vertical velocity is obtained. The computed zonal mean vertical velocity is shown for a few selected days of 2003–04 and 2005–06 in Fig. 6. From the figure, we can infer that the momentum flux convergence induces downward winds at mid-latitudes and upward winds at low-latitudes. It may be noted that in the case of 2003–04 (top panels), the vertical winds are larger on day numbers 45 and 49 (when poleward temperature is larger at 1 hPa than at 10 hPa) than on 57. The PV flux is proportional to the divergence of the EP flux vector. Earlier, GCM results of Thuburn and Craig (2000) showed that the convection top height could be influenced by the stratospheric meridional circulation. The convective activity over equator is influenced though the PV intrusion, which is popularly called 'downward control'. The PV advection at a given altitude will generate a response in the geopotential tendency whose vertical scale (measured in pressure units) is inversely proportional to wavelength. Thus, for example, upper-level vorticity advection associated with disturbances of large horizontal scale (small k), as in the present case, can generate geopotential tendencies that extend down to the surface with little loss of amplitude (Holton, 2004). As suggested by Eguchi and Kodera (2007), the enhanced wave activity associated with the SSW events could affect the meridional circulation in the tropical stratosphere and troposphere, which may lead to enhancement of tropical convection.

3. Discussion and conclusion

The major SSW events occurred during the years 2003–04 and 2005–06 are considered to investigate changes in the equatorial troposphere in response to the circulation changes caused by the SSW events. The increase in the poleward temperature difference is accompanied by a decrease in OLR over EQ and ESH averaged for the longitudes 90°E–150°E (Indonesian sector) indicating development of deep convective activity. The time variation of OLR values suggests that ENH also shows high, but relatively less convective activity than the EQ and ESH.

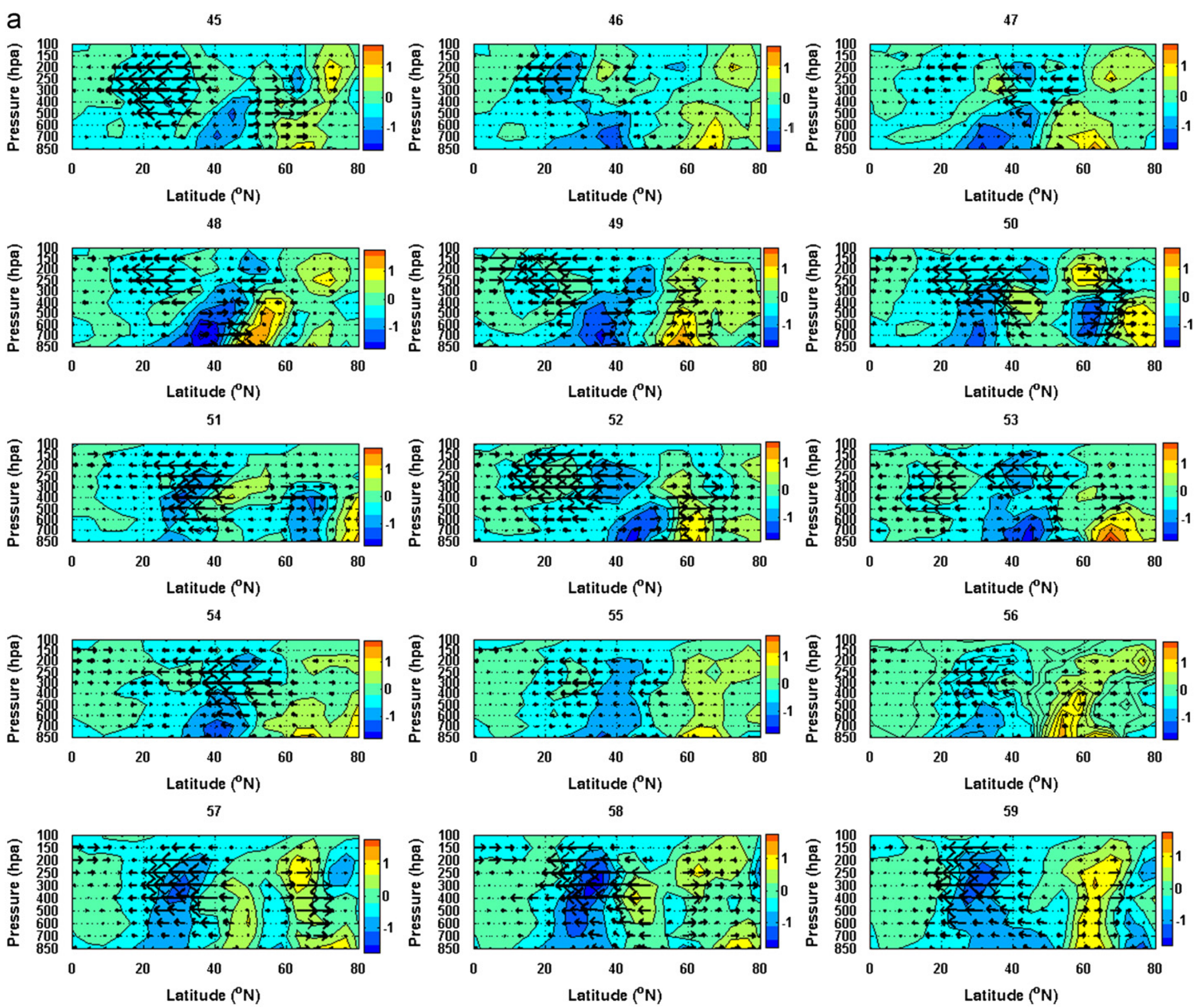

Fig. 5. (a) Latitude-height cross section of Eliassen–Palm vector and its divergence (10^{-4}m/s^2) for the days 45–59 for the year 2003–04 (day number 1 is 01 November 2003). The divergence of EP flux is shown as contour form. (b) Same as (a), but for the days 38–43 and 75–83 for the year 2005–06 (day number 1 is 01 November 2005).

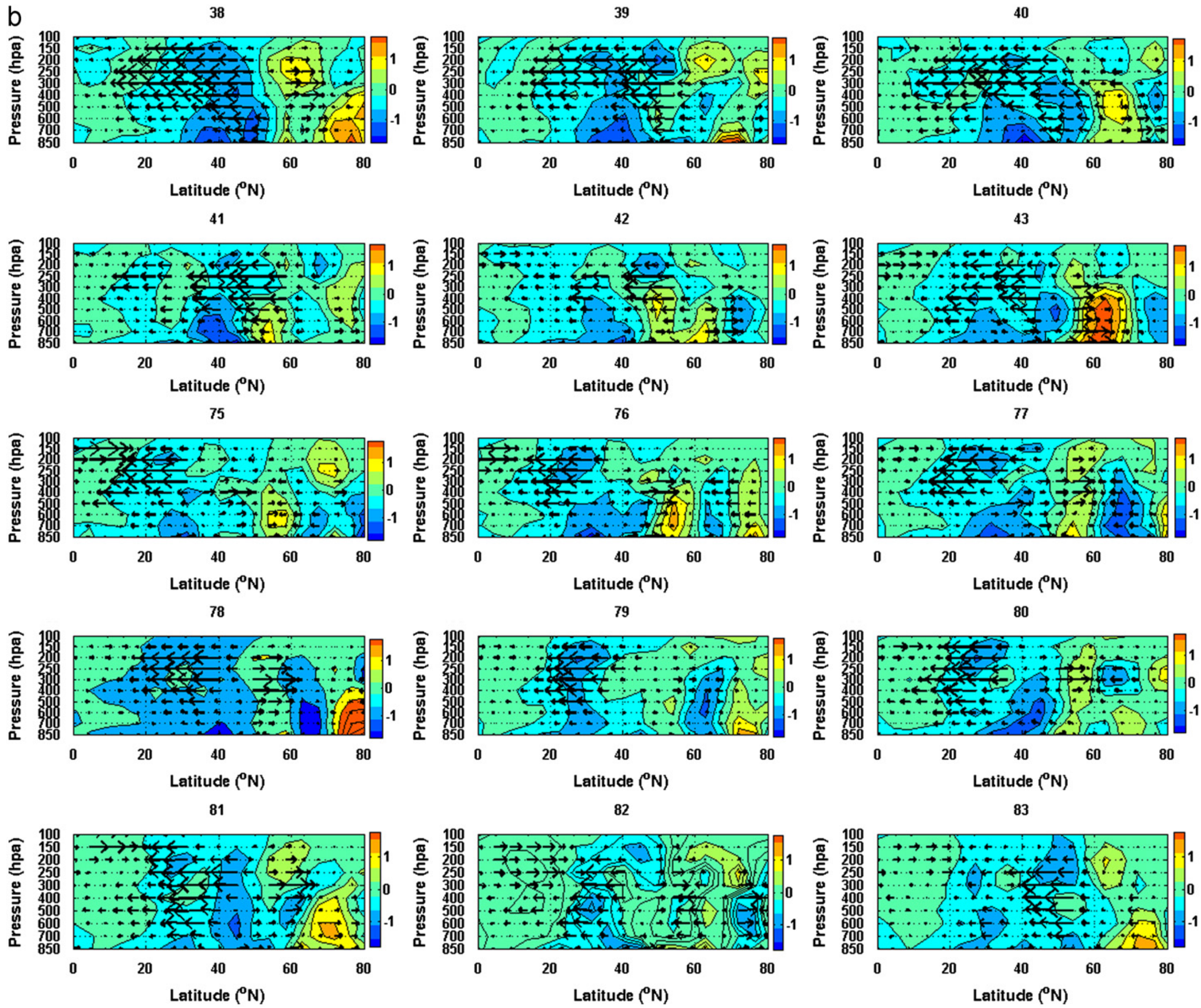

Fig. 5. (*continued*)

Earlier, Kodera and Yamada (2004) investigated the impact of the southern hemispheric major SSW held during September 2002 on the Hadley circulation. They found that the warming event induced equatorial upwelling and polar downwelling and noted that the impact was very small on the average intensity of the convective activity. They also observed that the convective activity in the equatorial region shifted towards southern hemisphere following the SSW. Similar results were obtained by Kodera (2006) in the composite analysis of 12 northern hemispheric stratospheric warming events that the convection in the ENH decreases and that over ESH increases following the SSW event. Unlike noted earlier by Kodera (2006), the present study (see Fig. 1) shows that the zonal mean OLR decreases (increases) with time indicating more (less) convective activity over ESH (ENH), which merely shows the southward migration of inter-tropical convergence zone and it does not show notable relationship with the major SSW events. The results of the present study also show that the convective activity in both hemispheres over Indonesian sector drastically increases, which can be noted by decrease in OLR during the warming events. The convective activity decreases after the warming events. It is found that there is an intrusion of high potential vorticity at 100 hPa in the longitude band 90°E–150°E during these two warming events. Earlier, Waugh and Polvani (2000) showed that climatologically, PV intrusions nearly always precede occurrences of deep convection in the tropical eastern Pacific. They showed that the PV intrusions were preferably in the longitude band 200°E–250°E. However, present study shows that PV intrusions also occur just west of 100°E in the two events (2003–04 and 2005–06). Besides, PV intrusion with less magnitude also occurs in the southern hemisphere in the longitude band 100°E–150°E. In the case of 2003–04, the PV intrusions west of 100°E and east of 200°E turn eastward and westward, respectively, while approaching equatorial latitudes and converge in the longitude band 100–150°E. In the case of 2005–06, the convergence is not so evident. However, PV intrusion is clearly observed at longitudes just west of 100°E and more at east of 200°E. Kiladis and Weickmann (1992) proposed that the relation between PV intrusion and convection occurs as a result of decreased static stability and enhanced upward motion in the area of positive vorticity advection ahead of the intrusive trough. Hoskins et al. (1985) showed that a positive (cyclonic) upper-level PV has a less stable potential

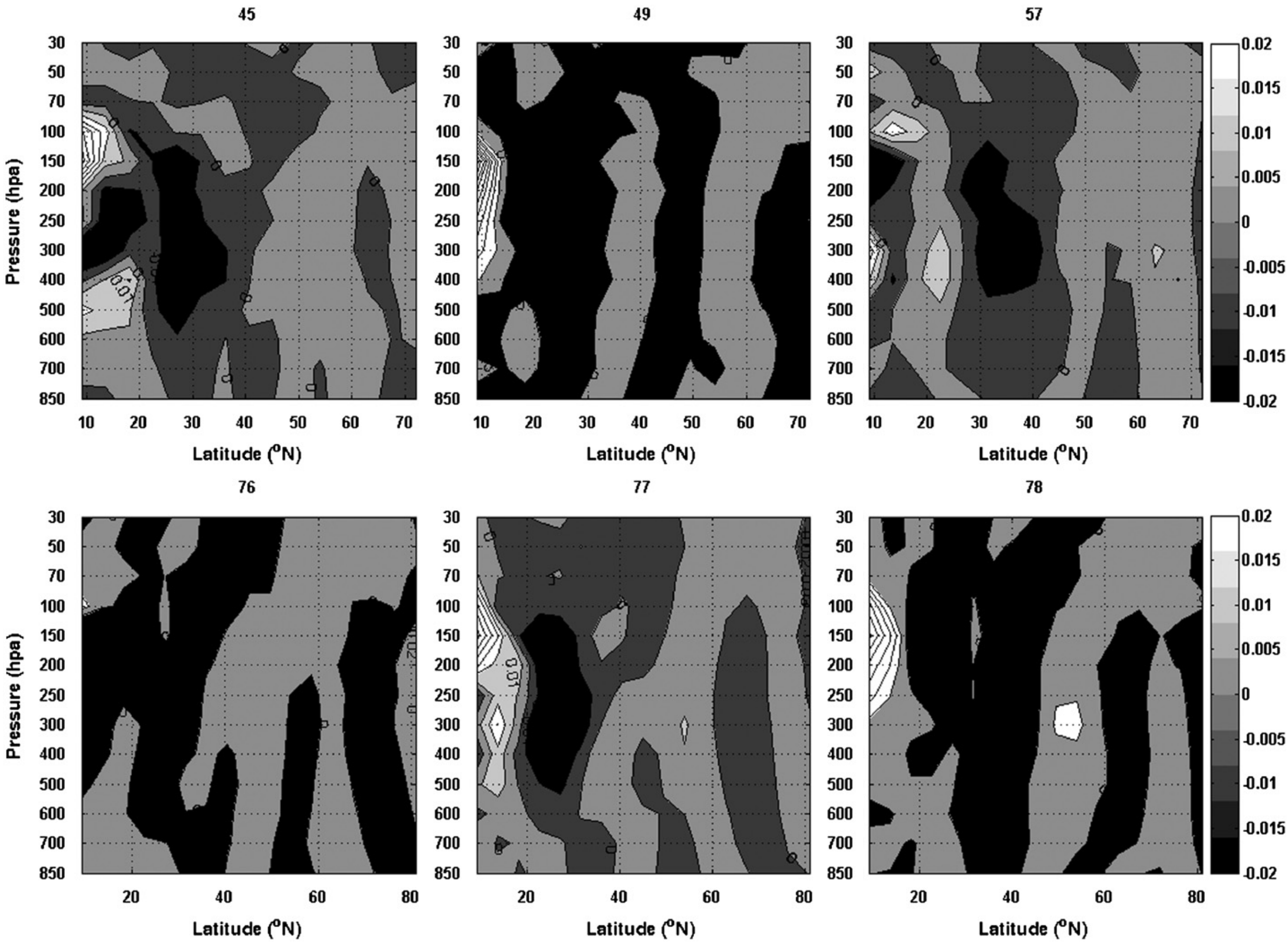

Fig. 6. Computed vertical velocity (m/s) for a few selected days in the years 2003–04 (top panels) and 2005–06 (bottom panels).

temperature distribution within and immediately below the anomaly. The decrease in static stability, together with the translational motion of the anomaly itself, results in a vertical motion at lower levels.

The large convective activity occurs, when maximum temperature difference is observed at 1 hPa in the case of 2003–04 and 10 hPa in the case of 2005–06. It may be noted that the temperature difference is larger at 1 hPa than at 10 hPa during 2003–04. In order to understand the difference in the response at low-latitudes between the two SSW events, EP flux and its divergence are used. The EP flux vectors clearly show more equatorward penetration on the day of peak warming at 1 hPa than at 10 hPa during 2003–04. However, more equatorward penetration of EP vectors is observed on the day of peak warming at 10 hPa instead of 1 hPa during 2005–06. Rather than peak warming days at different pressure levels at high latitudes, the extent of convergence of planetary wave (EP) flux to deeper lower latitudes seems to determine the level of convection at equatorial latitudes. Garcia (1987) studied the mean meridional circulation of the middle atmosphere for steady and time dependent forcing using a zonally averaged, quasi-geostrophic meridional Eulerian model. For short-term variation in EP flux divergence, which can be produced by interference between stationary and traveling waves, high-latitude stratospheric warming and tropical cooling are produced by a strong circulation (clockwise) extending below the forcing level (35 km altitude, 45°N latitude). From their figure 11, we can note that the high latitude troposphere and stratosphere are characterized by poleward and downward motions and equatorward and upward motions in the equatorial upper troposphere and lower stratosphere. Though their model does not contain Hadley circulation, it demonstrates that continuity requires that the stratospheric circulation affects the tropospheric, even tropical, circulation. The GCM results of Thuburn and Craig (2000) showed that the influence of the stratospheric circulation could be extended down to at least 5 km below the tropical tropopause.

The present study shows that the convergence of PW flux at low-latitudes during major SSW events can induce zonal mean upward winds at lower latitude troposphere. However, it may not be so effective in causing deep convection, which could reflect in zonal mean OLR. The potential vorticity advection as a narrow filament generates considerable upward vertical velocity to form deep convection and thick clouds, which reflect in the decrease of OLR. The potential vorticity advection to low-latitudes is more important in the generation of low-latitude convection than the peak of warming days at different high latitude pressure levels. Latent heat release in deep convective regions in the tropics is a very important source of energy for the general circulation of the atmosphere and non-migrating tides and gravity waves generated from this can produce profound changes in the thermal structure and mean circulation at higher altitudes (Sridharan et al., 2009).

Acknowledgements

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