Reply to Reviewer #1

Thank you for your valuable comments. We modified the manuscript according to your comments.

1. p2265, line 26- Please state the geographical location of the seesaw pattern of convection - it approximately zonally symmetric?

Reply: Kodera (2006) described only the zonal mean. The original sentence was not clear, so we modified as follows.

, which leads to a seesaw pattern of convective activity, an enhancement of convective activity near the equatorial southern hemisphere (10°S-equator) and a suppression in the tropics of the northern hemisphere (5°N-15°N).

2. p2266, line 24: Please state the horizontal resolution and the vertical resolution in the upper troposphere and lower stratosphere (refer to 2.6).

Reply: We inserted the following sentences in line 24, p2266.

The horizontal resolution of the ERA-Interim data is 2.5° × 2.5° in latitude and longitude and it has 37 levels (see section 2.6 for detailed levels in the upper troposphere and the stratosphere).

3. p2267, line 14: Since ECMWF data are being analyzed, it might be good to directly evaluate the diabatic heating term, which would then help diagnose whether the vertical heat fluxes are reasonable. This would also help resolve whether convective bursts can *cause* cooling in the TTL, or if only extratropical wave drag can cause such cooling.

Reply: There is no product of the diabatic heating term in ERA-interim data. We can calculate the diabatic heating from water vapor condensation and radiative heating. However, the accuracy of water vapor content is in doubt in the TTL and stratosphere. Additionally, radiative heating in the TTL is difficult to estimate correctly. Therefore we did not use other types of diabatic heating than residual.

4. p2267, line 18: Are the first and fourth terms always small? Is it self-consistent to leave out the fourth term on the rhs of (1) but explicitly discuss the importance of F_1^(phi) for the EP flux? (They represent the same term in the TEM transformation, where it is subtracted from the temperature equation and added to the zonal momentum equation.)

Reply: The first and fourth terms come from the meridional advection of potential temperature in Eulerian mean equation $(-a^{-1}\bar{v}\bar{\theta}_{\varphi} = first\_term + fourth\_term)$. Thus the sum of these two terms is negligible in quasi-geostrophic approximation, because the zonal mean of geostrophic wind is zero. We calculated these terms and confirmed both terms are indeed small. Usually, these terms are smaller than other terms by four or five orders of magnitude.

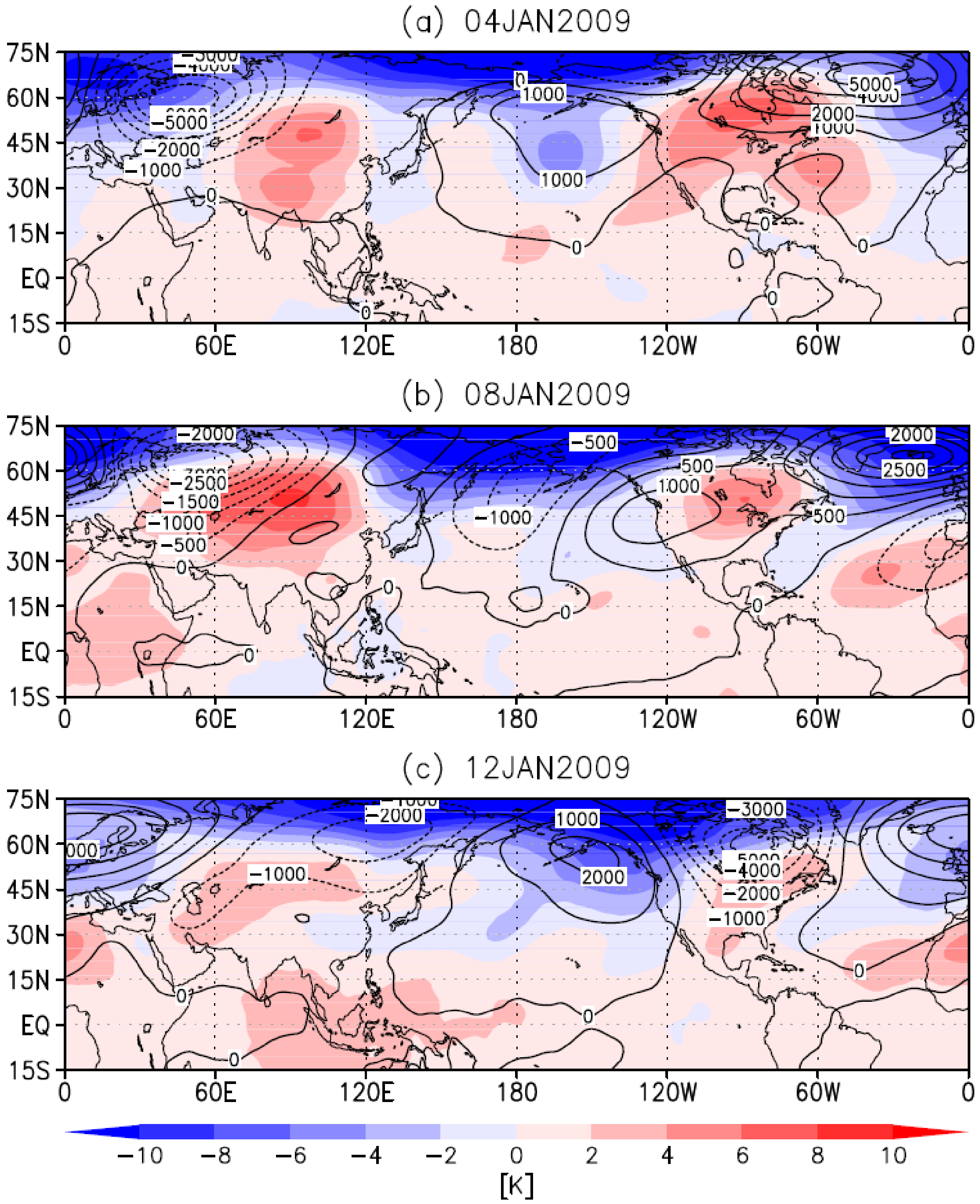
5. p2268, line 16: The TEM equations apply on a sphere and the flow need not be quasi-geostrophic, just hydrostatic.

Reply: That is true that the TEM equations apply on a sphere and flow need not be quasi-geostrophic. But, the sentence in line 16 is for the longitudinal integration of wave activity flux (6), so the original sentence is valid.

*6. Fig. 1 interpretation: There is a tropical warm anomaly centered at 50-70 hPa during January 1-16, which precedes the warming. It would be interesting to explore the geographical distribution of this warm anomaly and try to see how it could relate to a planetary wave connection to higher latitudes. Maybe there is a tropical precursor to the high latitude development. Note that the cooling near 10 hPa begins on January 10 at low latitudes at the same time as warming begins at high latitudes. (p.2272, l.1 states that the change begins on January 18, but that is in the middle of the transition.) On p. 2272, l16-17 The upward flow begins around 12 January, peaking near 19 January.

Reply: We showed anomalies of temperature and geopotential in Fig. R1.1. There is warm anomaly around equatorial Indian Ocean and Western Pacific on 12 January 2009. It might be related to strong convection there (see Fig. 11). We did not find out any clear connection between warm anomaly in the tropics and planetary waves in the extratropics.

Strictly assessing, polar temperature begins to increase on 13 January, and tropical temperature begins to decrease on 15 January (see Figs R1.2 and R1.3). However, from a broader perspective, it is no problem that increasing polar temperature and decreasing tropical temperature start around on 18 January.



(a) 04JAN2009

(b) 08JAN2009

(c) 12JAN2009

Fig. R1.1. Map of the temperature anomaly (color shading; K) and geopotential perturbation (contour; m^2/s^2) at 50 hPa. Here, the anomalies mean deviation from the mean values in January 2009, and perturbation means deviation from zonal mean here.

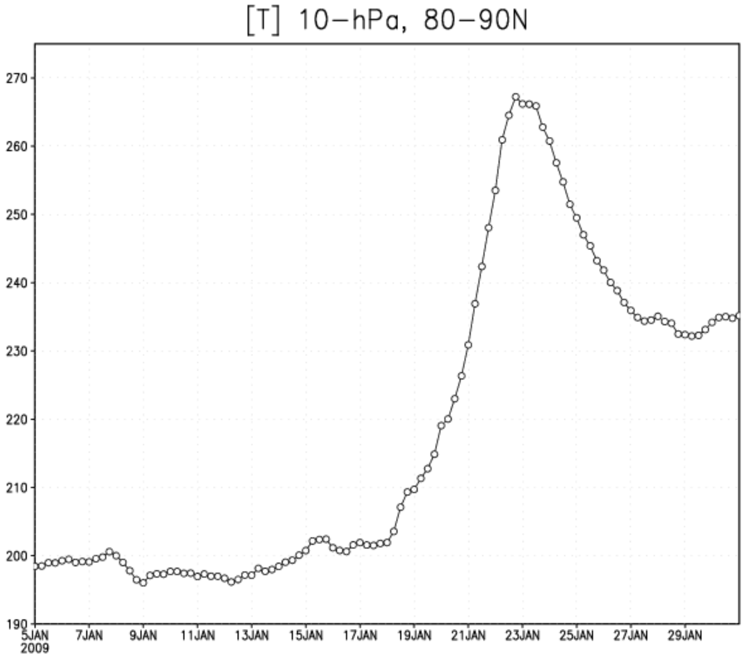


Fig. R1.2. Time series of Arctic mean temperature at 10 hPa.

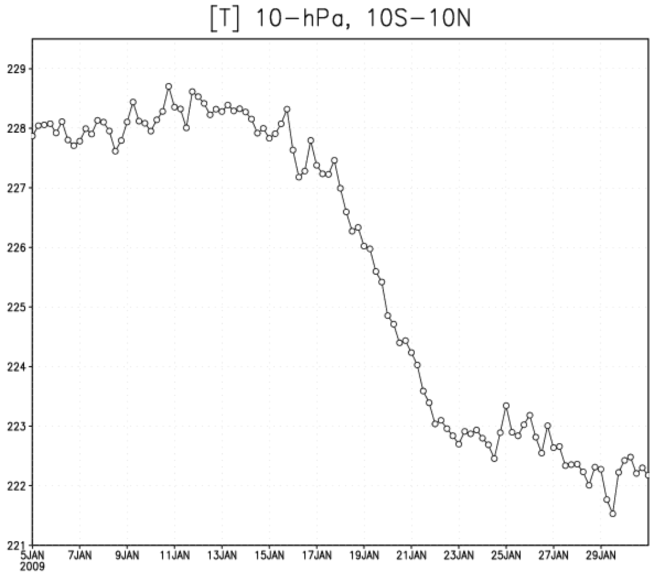


Fig. R1.3. Time series of tropical mean temperature at 10 hPa.

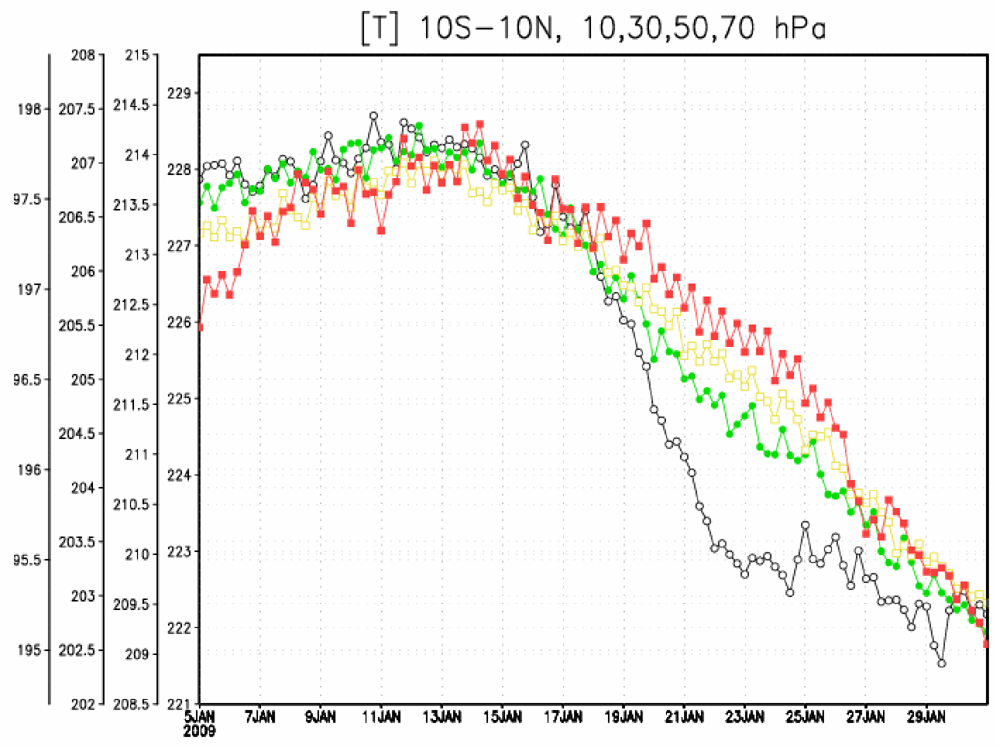


Fig. R1.4. Time series of the tropical mean temperature at 10 (black line; right axis), 30 (green line; second from right), 50 (yellow line; second from left), and 70 (red line; left) hPa.

7. Fig. 2 interpretation: The vertical motion changes at 10 hPa seem decoupled from those at 125 and 150 hPa, while the changes seen at 70 and 100 seem to act independently also. This seems to reduce the likelihood that far-field wave driving patterns exclusively control tropical upwelling ("the extratropical gyroscopic pump"). For example, p.2273, l23-24: If div F_1ˆz from NH forcing above 80 hPa controls tropical ascent in the stratosphere, please show this term and show what altitude ranges and times are influenced this way. On p. 2274,l5 it is stated that "tropical ascent is driven by global forcing below 90 hPa", so that the stratospheric pump "has only a minor influence on vertical flow between 150 and 100 hPa". On p.2276, l.2-5 it states that wave driving in the low latitude subtropics is the main factor inducing tropical upwelling in the UTLS.

Doesn't this imply that the "extratropical pump" is not the primary factor? How does this fit in with vertical fluxes of heat in the tropics? Please reconcile and clarify your views on the timing and forcing locations for vertical motion events in the tropics. If possible, it would be good to pin down the geographical location of enhanced ascent, for linking with OLR.

Reply: We add Fig. R1.5 in the revised manuscript (Fig. 3 in the revised manuscript). Fig. R1.5 shows how and where tropical upwelling is induced by stratospheric forcing and tropospheric forcing. Stratospheric forcing induced tropical upwelling above 150 hPa. However, the upwelling below 100 hPa is weaker than that driven by tropospheric forcing.

Around on 18 January, upwelling is generated over 60W-10E and at 100E (Fig. R1.6). However, time series of $\overline{w}$ and $\overline{w}^*$ are different (see Fig. R1.7), and time changes in $\overline{w}$ is opposite to that in $\overline{w}^*$ around on 18 January. Thus, we cannot explain the cause of increasing $\overline{w}^*$ by horizontal distribution of w.

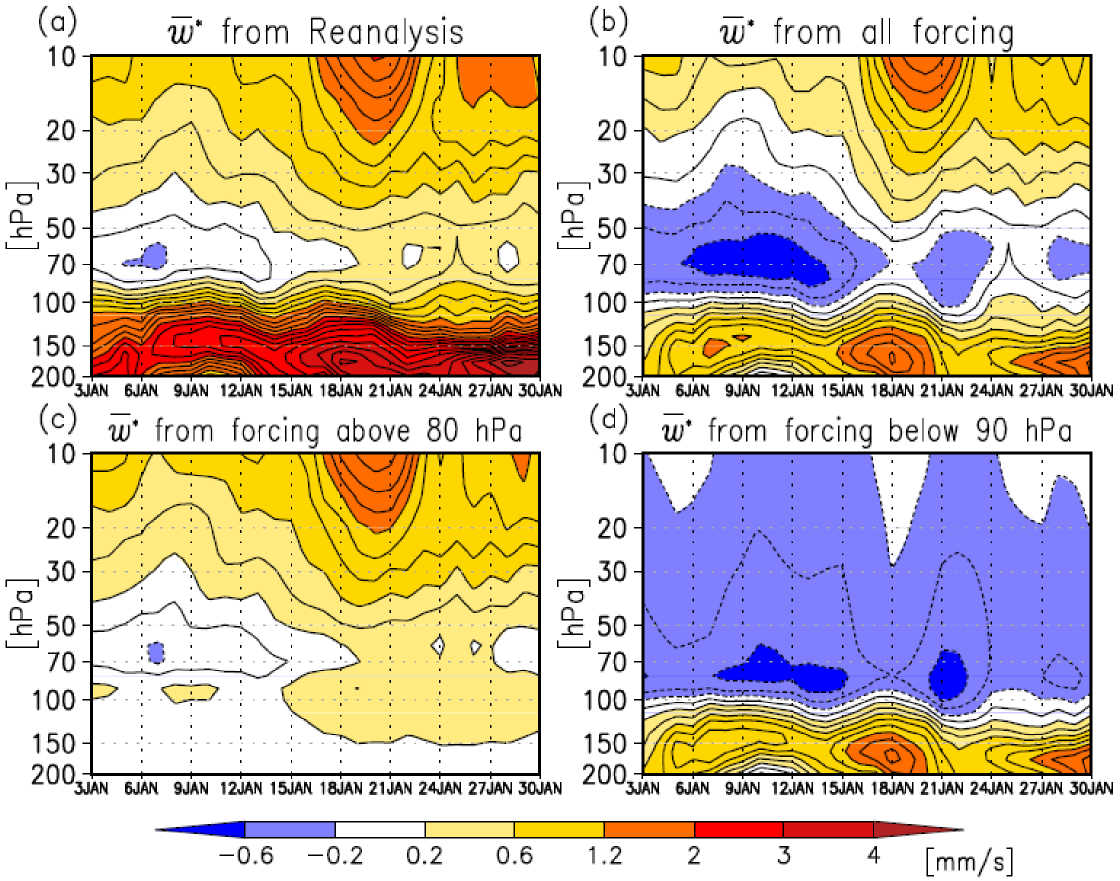


Fig. R1.5. Time–altitude section of the residual mean vertical wind (mm s^{-1}; color shadings and contours) based on all forcing. (a) Observation, (b) forcing in all regions, (c) forcing in the global stratosphere, and (d) forcing in the global troposphere. See Table 1 for detail.

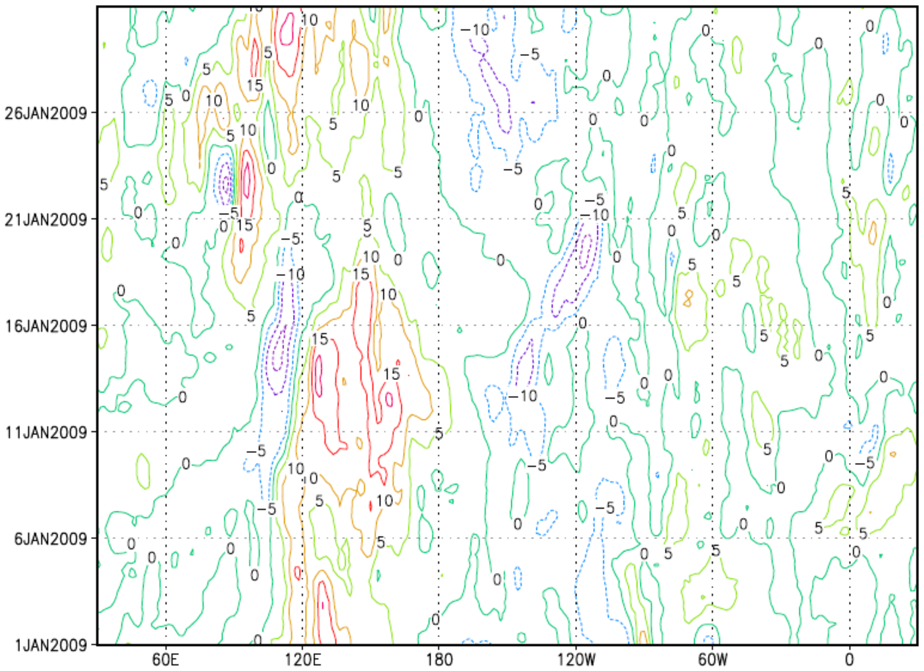


Fig. R1.6. Time-longitude section of latitudinal mean (10°S-10°N) *w* [mm/s] averaged over 150-100 hPa.

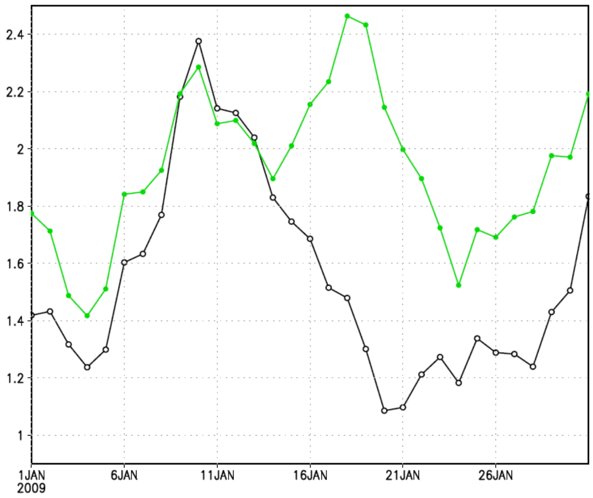


Fig. R1.7. Time series of $\overline{w}$ (black) and $\overline{w}^*$ (green) [mm s^{-1}] averaged over 150-100 hPa.

8. p.2274, l7: What is the physical interpretation of boundary forcing in the TEM set?

Reply: Physical interpretation of the boundary forcing is effect of the meridional eddy heat flux at the bottom and observed residual mean vertical wind at the top. Boundary value at the bottom is given by meridional divergence of the meridional eddy heat flux (the second term of definition of residual mean vertical wind) $\frac{1}{a\cos\phi}\frac{\partial}{\partial\phi}\left(\cos\phi\frac{\overline{v'\theta'}}{\overline{\theta}_z}\right)$.

9. p.2275, l20: Here it is stated that eddy forcing in the SH troposphere has an insignificant effect on the tropical tropopause layer, but Fig. 7a shows significant influence with upward motion at 200 and 150.

Reply: That is true. But the TTL here is defined as 70-150 hPa layer. Thus the SH troposphere has an insignificant effect above 150 hPa. The expression "significant" may be confusing. We modified (added) the following sentence in line 21.

.. has an small effect on the TTL, but has a large effect below 150 hPa.

10. p.2276, l26: From *10* January ...

Reply: That is true. We changed that line as follows:

From 10 January to 16 January, $F_1^{(z)}$ *is amplified in the mid-latitude troposphere,*

11. p.2278, l23: Please link to Fig. 10c. It looks to me like upward motion is induced off Baja California, but the OLR minimum is over Amazonia. Is an extended wave train connecting the two regions?

Reply: As you pointed out we also speculate that equatorward propagation of EP flux off Baja California in Fig. 10c might be related to the enhanced convection over Amazonia in Fig. 11c,d. However, since there is no clear evidence to prove that, we did not state that.

12. p.2280, l14-15: Is it possible to describe more about how the vertical heat fluxes relate to the structure of wave/monsoon structures in the tropical UTLS?

Reply: The lower part of the TTL over the convective region is generally warmer than the zonal mean ($\theta' > 0$) and the vertical motion is upward ($w' > 0$). Thus vertical heat flux is positive ($w'\theta' > 0$) there. In contrast, the upper part of the TTL over the convective region is generally colder than the zonal mean ($\theta' < 0$) and the vertical motion is upward ($w' > 0$), and thus, vertical heat flux is negative ($w'\theta' < 0$) there.

For schematic illustration in the upper part of the TTL, see Fig. R1.8, below.

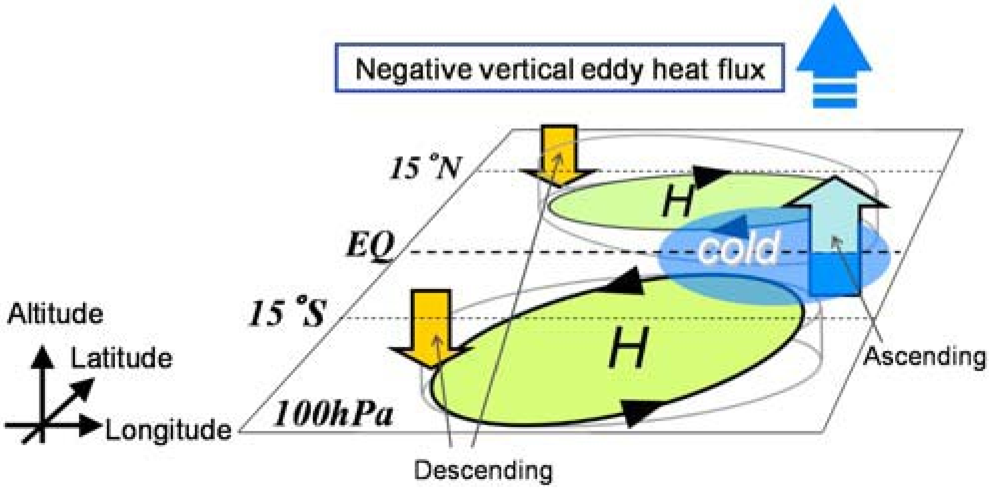


Fig. R1.8. From Figure 10 in Yoshida and Yamazaki (2010)

13. p.2280, l18-19: If subtropical wave driving is the proximal cause, then the SW was not the cause of tropical cooling.

Reply: As you pointed out, SSW did not drive upwelling in the TTL. However, Tropical upwelling in the stratosphere was induced by the stratospheric wave forcing, and subtropical waves caused upwelling in the TTL have the same source region as upward-propagating wave caused the SSW.

14. Figure 6 caption: Please clarify the difference between what is being shown in the upper versus lower panels.

Reply: The top panels are those for EP flux, but the bottom panels are $F_1^{(z)}$ component only. The $F_1^{(z)}$ component is dominant. Thus the top panels are similar to the bottom panels. We modified the figure caption.

15. Fig. 8: Tropical upwelling at 100 hPa is large on 18 January, larger than on 26 January, and it happens before the peak of the SW.

Reply: That is right. We added the following sentence in line 13 of page 2276 in the revised manuscript.

Tropical upwelling at 100 hPa on 18 January is larger than that on 26 January, and it happens before the peak of the SSW.

16. Fig. 10: Please plot to 10S so can see tropical upwelling and relate to Fig. 11.

Reply: We show a figure which has broader latitudinal range (see Fig. R1.9). However, we cannot plot wave activity flux near the equator because Coriolis parameter $f = 0$ at the equator.

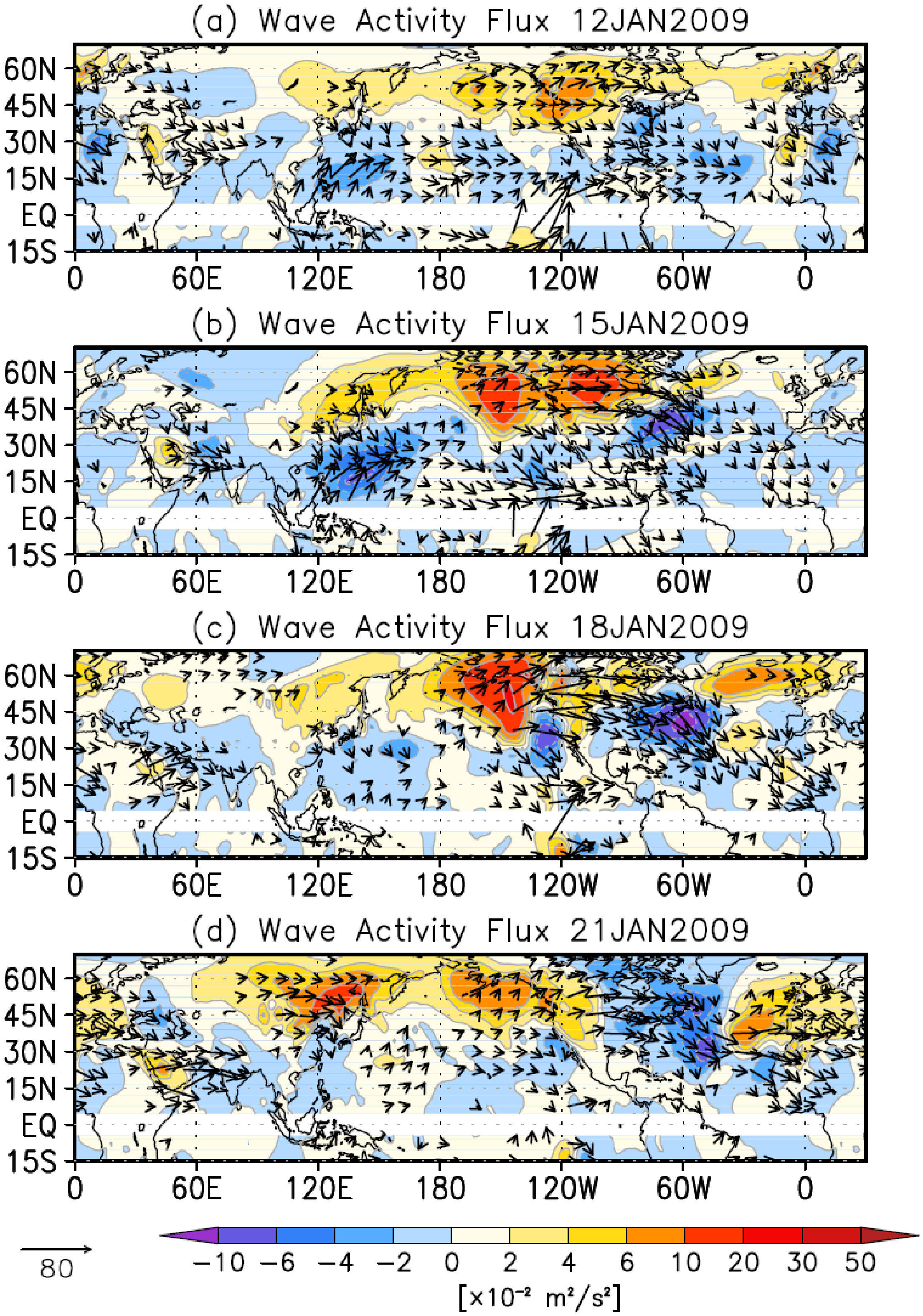


Fig. R1.9. Same as Fig 11 in our manuscript but for broader latitudinal range.