On the Turbulent Mixing and Ozone Variations in the Tropical Tropopause Layer associated with Kelvin Waves

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1. Introduction

In the tropical atmosphere, it is known that equatorial waves can largely perturb the tropopause structure; one big perturbation is due to Kelvin waves. Recently, *Flannaghan and Fueglistaler (2011)*[1] put a focus on turbulent mixing by shear-flow instability in connection with Kelvin waves. However, their discussion is based on the reanalysis dataset with a rather coarse vertical resolution (~1.5 km). Also the model schemes have uncertainty, thus the observational study needs to assess the features. Here, we explore the ozonesonde archive with a high vertical resolution (~0.2 km) which is provided by SHADOZ project (as described in Section 2) in terms of dynamical structure of Kelvin waves seen near the TTL. Because photochemical life time of ozone in the TTL is about months, so that this can be used for the tracer of atmospheric motion. *Fujiwara et al. (1998, 2003)*[2,3] and *Koishi and Shiotani (2012)*[4] have already suggested the importance of turbulent mixing, although their interpretation is based on a few observation results. To overcome the shortcoming of the limitation of spatial and temporal coverage of ozonesondes, composite analysis is applied. This will be enables us to describe the behaviors of ozone associated with Kelvin waves. Furthermore, to avoid the influence from the vertical advection accompanied by the waves, the ozone variation in the isentropic coordinate is studied. Finally we discuss about the transport process and mechanisms associated with the waves.

2. Data

We analyzed ozonesonde profiles between 10 degrees bands from the equator of 10 observation stations; they are provided by SHADOZ (Southern Hemisphere Additional Ozonesondes). About 3000 vertical profiles of ozone and temperature are interpolated to 0.2 km vertical bins. To categorize the phase of Kelvin waves, we used temperature (T) and zonal wind (U) data at 100 hPa level from the ERA-Interim dataset provided by the ECMWF for the period 1998 to 2009.

3. Method

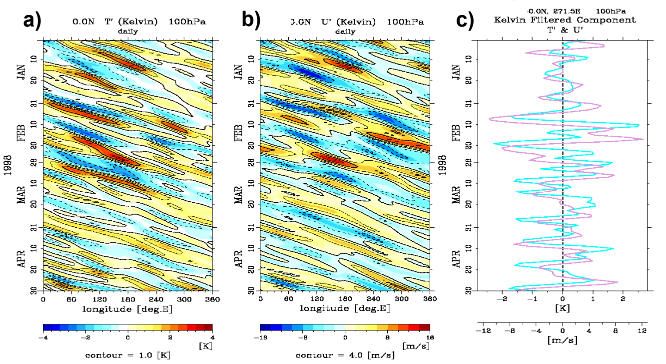

Figure 1. Longitude time sections of (a) 100 hPa temperature anomaly , (b) 100 hPa zonal wind anomaly, and (c) their time series at 271.5 degrees east calculated by Kelvin wave filtered component of ERA-Interim.

Longitude-time sections of filtered 100 hPa temperature anomaly (T') and zonal wind anomaly (U') are shown in Figure 1 (a) and (b). The filter is applied by the zonal wave numbers 1 to 10 and the period from 4 to 23 days in the spectral-frequency domain (same as *Suzuki and Shiotani (2008)*[5]). The time series of T' and U' at 271.5 degrees east are shown in Figure 1 (c). We can see T' (light blue line) leads U' (pink line) by about a quarter cycle at fixed location. Then we use these time series at 10 locations, which is corresponding to 10 observation stations provided by SHADOZ, for calculating wave properties.

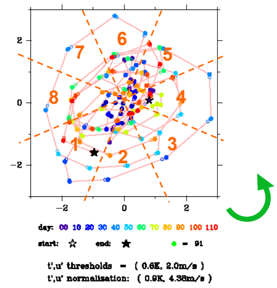

Figure 2. Normalized T'-U' diagram.

Figure 2 is an example of the normalized T'-U' diagram. The trajectory using the time series of Figure 1 rotates anticlockwise in the T'-U' plane, indicating the signal of eastward traveling waves in this location and period. Because it is theoretically expected that the T' is in quadrature with U', we can identify the phase of Kelvin waves from this diagram. After we put the phases into 8 categories, we made composite analyses for the ozone and temperature profiles in terms of the phase evolution of Kelvin wave.

4. Results in the height & isentropic coordinates

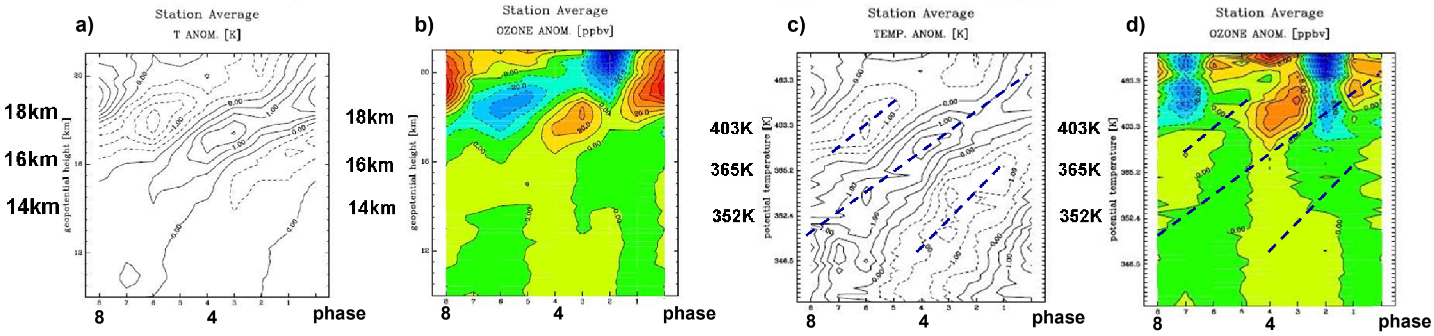

Figure 3. Phase-height cross sections of composite anomaly from level average in the height coordinates (a,b) and composite anomaly from level average in the isentropic coordinates (c,d) all using SHADOZ data. Temperature (T) anomaly are drawn in (a,c) and ozone (O3) anomaly are drawn in (b,d). Negative values are indicated by dashed lines. Thick dashed lines in (c) and (d) represent maxima and minima of the T anomaly. Red color represents positive O3 anomaly [ppbv].

Figure 3 show four pictures of the phase-height and the phase-isentropic cross sections of temperature (T) and ozone (O3). In these cross sections or, in other words, the longitude-height cross sections for eastward traveling Kelvin waves, the composite temperature profiles show clear warm and cold anomalies in relation to the Kelvin wave in (a). The phase line of T anomalies tilts eastward, indicating the downward phase propagation of the Kelvin wave structure. For the O3 composite, deviations from the height average also indicate the downward phase propagation in (b). This in-phase relationship between T and O3 is probably due to vertical advection. Because the undulation of isentropic surfaces associated with Kelvin waves should not be negligible in the height coordinate, we also described the O3 variations on the isentropic surfaces. Figure 3(d) clearly shows there is a non-conservative area in the phase-isentropic cross section, implying the evidence of non-adiabatic transport process.

5. Fundamentals of inducing turbulence

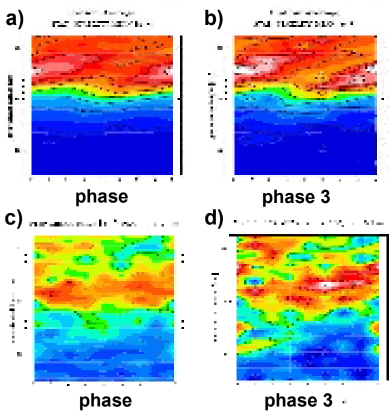

Figure 4. Phase-height cross sections of statistic stability (a,b) and vertical wind shear (c,d). Wave amplitude larger than equal 1 and 2 are shown in (a,c) and (b,d), respectively.

In the isentropic coordinates as seen in Figs.3(c) and 3(d), the T anomalies still show the phase progression associated with Kelvin waves. As for the O3 anomalies, however, the phase progression disappears, but the enhancement of O3 can be seen in the warm phase around just above 400 K level. Focusing on the positive O3 anomalies above 400 K level (phase3-4), the enhancement of O3 corresponds to the transition from plus to minus T anomalies. This suggests that the turbulent mixing may occur in the shear zone particularly for the warm anomaly rather than the cold anomaly. *Nishi et al. (2007)*[6] also supports this kind of transition of the Kelvin waves.

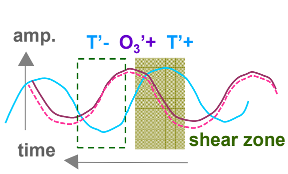

Figure 4 explores characteri-cteristics of atmospheric stability. Panels (a,c) show the same sections as in Fig.3. Panels (b,d) show the sections, when the large amp-litude is categorized. Peaks of both variables are seen near above 400K around phase 3, indicating the unstable states prefer this stage.

6. Conclusion

We investigated the observed variations of ozone around the TTL in relation to large-scale waves. These results provided the consistent picture between diffusion process and ozone enhancement in connection to Kelvin waves. Turbulent transport process should be clarified by future observations.

References

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