Formation of the double stratopauses and elevated stratopause associated with the major stratospheric sudden warming in 2018/19

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In some major stratospheric sudden warming (SSW) events, the stratopause once disappears after the warming and reforms at an elevated height (e.g., Siskind et al., 2007; Manney et al., 2008, 2009), which is called the "elevated stratopause" (ES). Tomikawa et al. (2012) showed that the ES forms and descends to the climatological height of the stratosphere due to the westward gravity wave forcing (GWF), while some studies indicated that planetary wave (s=1) forcing (PWF) is important for the initial formation of the ES (e.g., Limpasuvan et al., 2012). However, details are not well understood. Clarifying how the middle atmosphere is modulated responding to the SSW, it is effective to conduct a quantitative study by using a GW-resolving GCM that covers from the troposphere to the mesosphere and lower thermosphere (MLT).
In this study, using the outputs of the simulation of the 2018/2019 SSW event carried out by a GW-resolving GCM containing the MLT region, we analyzed dynamical phenomena occurred in the whole middle atmosphere. As a result, we found that the ES formed after the major warming on January 1 and a significant temperature maximum appeared in the polar upper mesosphere around December 28 prior to the ES formation, which is referred to as the "double stratopause" (DS). Then we focused on the formation of the DS and ES and analyzed the role of wave forcing in these phenomena.
First, the cause of the DS formation is described. A eastward jet existed at a latitude/height of ~30°N/~70km since 7 days before the DS formation, and the GWF is positive above and negative below the jet. On the polar side of this GWF>0, negative latitudinal gradient of potential vorticity (PV) is observed. Subsequently, PWF>0 and PWF<0 appeared, which act to eliminate the anomalous PV gradient. Therefore, plausible processes of the DS formation are that 1) the GWF makes a weak temperature maximum at higher latitudes, 2) the mean field becomes unstable, 3) and then PWs are generated and exert forcing which intensifies the temperature maximum in the polar upper mesosphere.
Second, the formation process of the ES is discussed. On January 10 when the ES formed, GWF was strongly negative in the polar upper mesosphere. The eastward jet is reformed in the polar mesosphere on that day. This means that critical level filtering by the jet causes GWF<0, which is important for the ES formation, as Tomikawa et al. (2012) suggested. Thus, we examined the recovery mechanism of this jet. Before the warming, stratospheric PWF was strongly negative, as commonly observed in SSW events. Near the equator, the stratospheric temperature decreased and a westward jet near the stratopause was accelerated. Negative GW and synoptic-scale wave forcing appeared at the bottom of and around the peak of this jet, respectively. On the polar side of this, the temperature increased at ~20°N. Around January 6, a eastward jet with its axis at ~40°N/~55 km formed on the polar side of this warming region. Meanwhile, the westward jet in the polar stratosphere and mesosphere was accelerated in association with SSW around January 8. GWFs above the two jets took large negative/positive values at lower/higher latitudes than 60°N. The temperature increased significantly at ~60°N/50–90 km corresponding the latitudinal boundary of GWF>0 and GWF<0. These results suggest that the recovery mechanism of the eastward jet is explained by following processes: 1) wave forcings become negative near the equator related to the temperature decrease and acceleration of the westward jet there associated with SSW, 2) the temperature increases at ~20°N due to the wave-induced residual downwelling and then the eastward stratospheric jet forms at mid-latitudes keeping the thermal wind balance, and 3) GWF<0 above this jet and GWF>0 above the westward polar jet associated with SSW cause strong downwelling at ~60°N and

reinforce the negative latitudinal gradient of the temperature in the high latitude region.

Keywords: Middle atmosphere, Stratospheric sudden warming

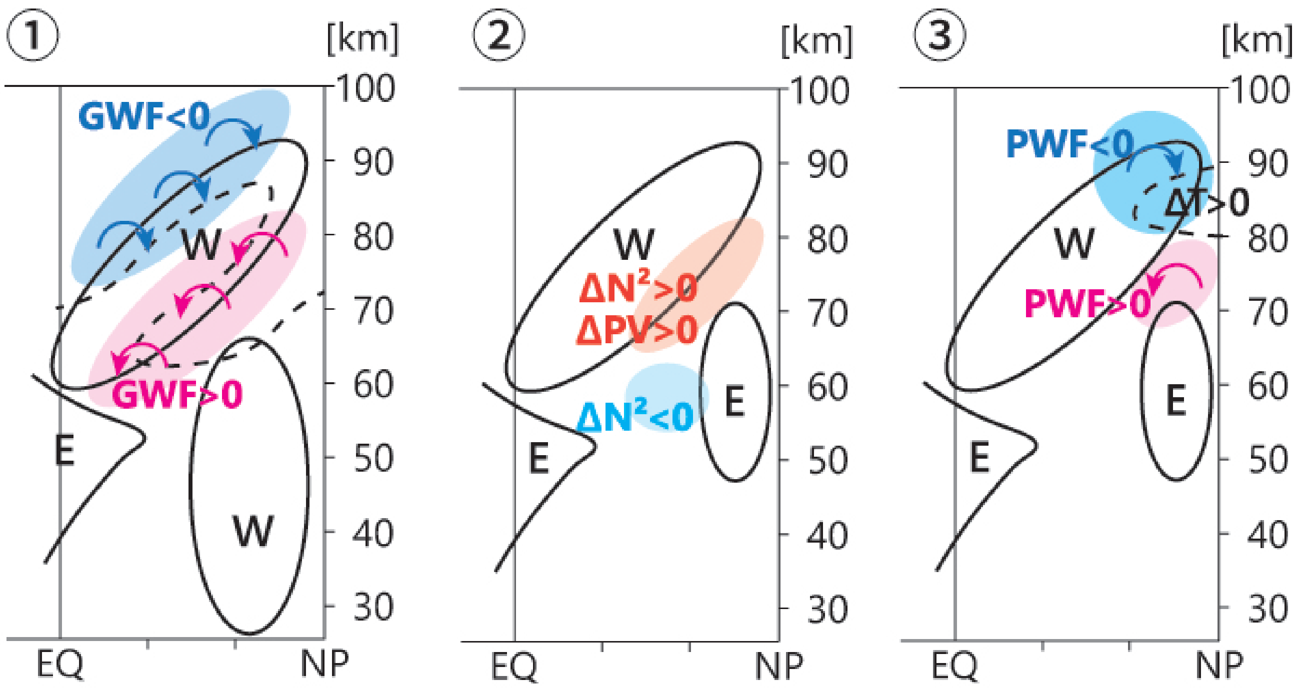

Figure 1 Schematic of the formation process of the DS.

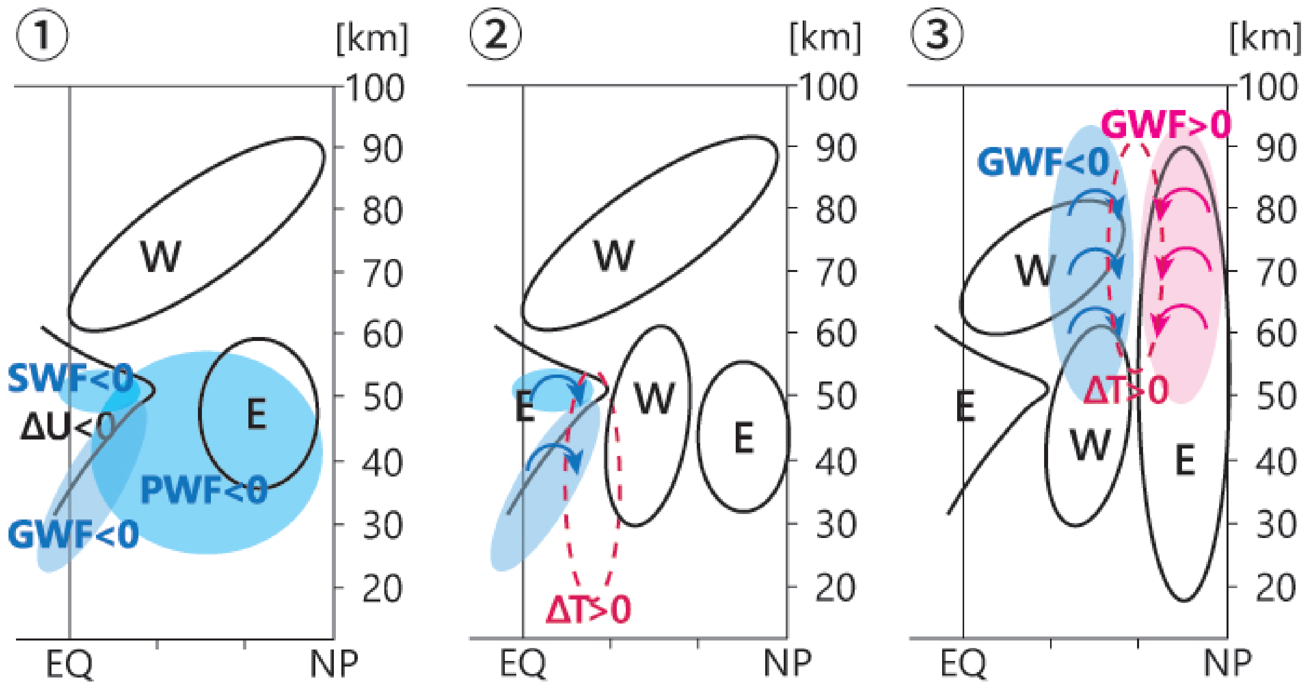

Figure 2 Schematic of the recovery mechanism of the eastward jet in the polar mesosphere.