

# A study on sources of gravity waves that reach the summer stratosphere and mesosphere based on high-resolution radiosonde data

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Gravity waves (GWs) are mainly generated in the troposphere and play a crucial role in the momentum transport in the stratosphere and mesosphere. Several possible main sources of GWs are suggested by theoretical, numerical and observational studies; topography and jet-front systems in winter, and strong convection in summer (e.g. Sato *et al.*, 2009). In addition, theoretical work by Bühler *et al.* (1999) indicated that the Kelvin-Helmholtz (KH) shear instability can cause significant emission of GWs in summer. Having critical layers in the lower stratosphere, orographic waves hardly propagate into the summer stratosphere and mesosphere. On the other hand, most GWs emitted from the KH instability above the tropopause jet do not encounter their critical layer and can reach the stratosphere and mesosphere. However, observational studies from this view point are insufficient. In this study, using high-resolution radiosonde data from 9 stations in Japan, the generation and propagation of GWs with short vertical wave length ( $\leq 4$  km) in the troposphere and lower stratosphere are investigated. The parameters describing the wave structure are estimated by a hodograph analysis. Drawing a comparison with GWs observed in winter, source and propagation characteristics of GWs in summer are highlighted. The latitude-height distribution of wave amplitudes and phase velocity characteristics suggests that orographic waves are not dominant in summer in contrast with those in winter. The vertical direction of wave energy propagation shows that summer GWs propagate upward and downward from the 10-15 km height region, where the occurrence frequency of the events with Richardson number (Ri) less than 0.25 (which is a necessary condition for the KH instability) is high. In addition, wave amplitudes in the lower stratosphere are relatively large above the peak of the occurrence frequency of  $Ri < 0.25$ , which is located around the latitude and height region of 30°N-35°N, 12-15 km. These results suggest that the KH instability is one of major sources of GWs in the summer stratosphere. The KH instability tends to occur when the vertical wind shear is large and the static stability is low. In summer, the vertical shear associated with the jet is stronger at higher latitudes and the static stability is lower at lower latitudes. The peak of occurrence frequency of  $Ri < 0.25$  as mentioned above is situated at the middle latitudes inbetween. Therefore, it can be inferred that this region is climatologically important for shear-generated GWs which can reach the summer stratosphere.

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