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Analysis of an Extratropical Cyclone and Tropopause Inversion Layer using a Meso-scale Model

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Tropopause Inversion Layer (TIL) is a persistent layer with high static stability (Birner, 2002). Formation mechanisms of the TIL are not well understood, though mechanisms which may contribute the formation have been proposed, such as a dynamical mechanism due to local vertical convergence associated with a synoptic vortex (Wirth, 2003) and a radiative forcing mechanism due to heating by ozone and cooling by water vapor (Randel et al., 2007). Most of the studies so far used some idealized simulations and numerical experiments with realistic conditions have not been conducted yet.

We perform numerical experiments on a life cycle of an observed extratropical cyclone with Non-Hydrostatic Model (NHM) of Japan Meteorological Agency (JMA), which is originally used for operational numerical weather predictions. The model we modified has 200 layers in the vertical from the surface to 25 km in altitude, and the horizontal domain is 4140 km x 4000 km around Japan with a horizontal resolution of 20 km. The time integration period is 72 hours from 19th to 22nd in February, 2009, during which a typical event of explosive cyclogenesis was observed. For the initial and boundary conditions, we use NCEP/FNL data.

The TIL obtained in the control run has similar characteristics as observation, including dependence on local relative vorticity (Birner et al., 2002): stronger TIL in negative vorticity areas and weaker TIL in positive vorticity areas. But the dependence is clear only at the developing and mature stages of the cyclone, which suggests that the evolution of the cyclone plays an important role in the formation of the TIL. In the model, stronger TIL tends to appear in the areas where stronger gravity waves exist. To see the effects of gravity waves on the TIL, vertical convergence at the tropopause is analyzed. The histograms of maximum buoyancy frequency square within the TIL ($N^2{}_{max}$) show that the regions of vertical convergence show higher $N^2{}_{max}$, whereas those of vertical divergence show lower $N^2{}_{max}$. This tendency is clearer in the regions of negative relative vorticities at the tropopause. By taking account of the fact that the gravity wave activities associated with the cyclone and the jet streak seems to be enhanced during the developing and mature stages of the cyclone, the vertical convergence by gravity waves associated with synoptic weather systems can be a key in the formation of the negative correlation between the strength of the TIL and the local relative vorticity at the tropopause.

In experimental runs, water vapor is removed above 300 hPa level (EXP300) and 500 hPa level (EXP500) in the initial conditions in order to investigate the temperature response to the radiative forcing by water vapor perturbations around the tropopause. The explosive development of the extratropical cyclone is not different from the control run very much, but the TIL becomes stronger in EXP300 and weaker in EXP500. The vertical profiles of static stability in EXP300 become sharper due to the shaper vertical water vapor profile with sudden decrease of water vapor just below the tropopause (that is, 300 hPa level in EXP300). Quantitative analyses on the formation of the TIL are performed in detail to see the relative importance of dynamical and radiative forcing mechanisms.

Keywords: tropopause inversion layer, extratropical cyclone, gravity wave