論文の内容の要旨

論文題目：Dynamical understanding of variabilities of polar stratospheric and upper tropospheric clouds

（極域成層圏・上部対流圏の雲変動の力学的理解）

氏名　髙麗　正史

There are unique clouds in the middle atmosphere in the polar regions, that is the polar stratospheric clouds (hereafter referred to as PSCs) and polar mesospheric clouds. The PSCs appear in the polar stratospheric winter and play a role in the significant depletion of polar stratospheric ozone. First, PSC particles serve as an environment for heterogeneous reactions that convert inactive chlorine and bromine reservoirs into reactive forms. Second, the uptake of HNO_3 into PSC particles and subsequent gravitational sedimentation of the particles remove reactive odd nitrogen from the lower stratosphere (i.e., denitrification). Atmospheric waves affect the PSCs in terms of occurrence frequency and composition because they modulate temperature in the polar stratosphere. The adiabatic warming/cooling associated with residual circulation driven by the wave forcing modifies temperature on large scales, which results in the modulation of the PSC occurrence frequency. Furthermore, a recent study suggested that as the stratospheric circulation becomes stronger, the cloud occurrence frequency decreases not only in the stratosphere but also in the upper troposphere on monthly-mean scales. This result implies that the stratospheric circulation can modify the radiative budget in the troposphere.

For better understanding of variability of the stratospheric and upper-tropospheric clouds in the polar regions, analyses on the effects of atmospheric waves are needed from two viewpoints of (i) temperature fluctuations associated with the waves and (ii) adiabatic warming/cooling with the stratospheric circulation driven by the wave forcing. For this purpose, we examine these clouds based on two kinds of satellite observations and reanalysis data.

In the first part of research in the present thesis, we examined the simultaneous appearance of PSCs and upper tropospheric clouds (UCs) in both hemispheres. Previous studies have reported that PSCs are frequently observed simultaneously with upper tropospheric clouds (UCs) over the Arctic and Antarctic. However, the mechanism of this simultaneous occurrence was not clarified. Furthermore, it has not yet been examined whether the UCs that simultaneously occur with PSCs are truly located below the tropopause, because the tropopause height is modified by tropospheric disturbances.

From a correlation analysis and a statistical dependence test, it has been shown that the simultaneous occurrence of clouds with an altitude range of 15–25 km and 9–11 km is statistically significant. This result suggests that the lower clouds are also located in the stratosphere, because the mean tropopause height is about 8–9 km. From an analysis using the altitude relative to the locally determined tropopause height, it is also shown that the PSC occurrence frequency is significantly correlated with the frequency of the clouds around and slightly above the tropopause. This means that the lower clouds should be regarded as tropopausal clouds (TPCs) rather than UCs.

It is also shown that the simultaneous occurrence of PSCs and TPCs is frequently associated with blocking highs having large horizontal scales (several thousand kilometers) and tall structures (up to a height of ∼15 km) causing deep negative temperature anomalies extending up to about 20 km. The longitudinal variation of blocking high frequency accords well with that of the simultaneous occurrence frequency of PSCs and TPCs. This fact supports the inference that the blocking highs provide a preferable condition for such simultaneous occurrence. It is also shown that dominant PSC composition depends on the longitude relative to the center of blocking highs. Ice PSCs are relatively rich above the blocking highs, while the proportions of NAT-rich and STS-rich PSCs are large leeward of and windward of blocking highs, respectively. It is confirmed that such relation among PSCs, TPCs and blocking highs is seen in both hemispheres.

In February 2011, when an unprecedented ozone depletion occurred over the Arctic, PSC frequency is highest of all analyzed years. The proportion of PSCs observed simultaneously with TPCs in February 2011 is lower than those in January in the other years. This result implies that the low temperature is not largely attributable to the above blocking highs in 2011. According to previous studies, this high PSC frequency is likely due to low stratospheric temperature related to low planetary waves activity in the stratosphere. A plausible explanation is that a blocking high appearing in the western Pacific region interfered with a climatological-mean trough, which resulted in significant suppression of the upward propagating planetary waves.

In the second part of research in the present thesis, the variability of upper tropospheric clouds in the polar regions during three SSW events in 2009, 2010, and 2012 is examined using two kinds of satellite observations and reanalysis data. It is newly revealed that cloud frequency in the upper troposphere (an altitude range of 8–12 km) decreased and downward displacement of mean cloud top heights occurred after SSWs. After the sudden decrease in upper tropospheric cloud frequency, increase both in temperature and static stability around the tropopause and a downward shift of the tropopause height are simultaneously observed. These changes in the upper troposphere are observed when the downward residual mean flow associated with SSWs becomes stronger around the tropopause level. Furthermore, by using a recent theory on three-dimensional residual mean flow and using a recently-proposed extended Hilbert transform, the relation between cloud frequency and residual mean flow is examined in horizontal maps. It is shown that the geographical regions where characteristic decrease in cloud frequency is observed accord well with those with strong downward residual flow. This result suggests that residual mean downward flow at least partly affects the horizontal distribution of cloud frequency in the upper troposphere. This suggests that the relation between the cloud frequency decrease and the downward residual mean flow, as seen in the zonal mean meridional cross section from the analysis using the TEM equation system, is observed even in the horizontal distribution.

Another interesting feature is that the low cloud frequency in the upper troposphere starting after SSWs continues for more than one month. It is considered that the slow radiative relaxation time scale in the lower stratosphere may be partly responsible for the long-lasting low cloud frequency. The change in the activity of tropospheric disturbances after SSWs may be another important factor causing the continuous low cloud frequency. However, the change of wave activity itself may be attributable to the static stability structure modified by the enhanced downward residual mean flow in association with the SSW events.

It is likely that SSWs play a major role in the dynamical coupling of the stratosphere and troposphere as discussed in many previous studies. Our results further indicate that the SSWs can affect the tropospheric radiative budget through the modification of cloud frequency and cloud top heights because outgoing long-wave radiation varies.