学位論文 (要約)

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)

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Abstract

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 imply 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.

要旨

極域の中層大気には、他の緯度帯では観測されない極成層圏雲 (Polar Stratospheric Cloud; 以下、PSC) や極中間圏雲といった固有の雲が出現する。PSC は冬季成層圏中下層の低温域に出現する。PSC は、雲粒上での不均一反応、及び、雲粒の落下による脱窒素作用という 2 つの過程を通して、春季の成層圏極域オゾン減少において主要な役割を果たす。したがって、オゾンホールの将来予測をする上で、PSC と大気場の関係を理解することは必要不可欠である。PSC の出現頻度や PSC 雲粒の組成への、大気波動による影響がこれまで指摘されている。第一に、惑星規模波や総観規模波、重力波に伴う低温領域において、PSC 出現頻度の上昇や雲粒の組成の変化が報告されている。第二に、これらの波動が駆動する成層圏子午面循環は、より大スケールの温度場を変調し、PSC の出現頻度に影響を与える。さらに、近年の研究で、月平均の時間スケールで成層圏循環の変動に対応して、極域対流圏上層の雲が変動することが報告された。このような雲の変動に伴って、対流圏の放射収支が変調される可能性がある。つまり、この結果は、雲変動を介した成層圏-対流圏結合の過程の存在を示唆するものである。

以上のように、極域冬季における成層圏・対流圏上層の雲の変動を理解するためには、大気波動の影響を、(i) 波そのものに伴う温度変動と (ii) 波強制が駆動する循環に伴う断熱昇温・降温の 2 つの観点から調べる必要がある。そこで、これらの雲と大気波動の関係を包括的に明らかにするために、衛星ライダー観測データ、GPS 電波掩蔽観測データ、及び再解析データを組み合わせたデータ解析を行った。

本論文の前半では、近年報告されている、PSC と対流圏上層の雲の同時出現について、その関係を検証し、そのメカニズムについて考察した。これらの異なる高度の雲が同時に出現することを報告する先行研究はあるが、そのメカニズムは明らかになっていなかった。さらに、PSC と同時に出現する雲がどの高度にあるのか、つまり、対流圏界面より下に存在するかという点も十分に検証されていなかった。

本研究では、これら 2 つの異なる高度の雲の関係を統計的に調べた。まず、相関解析と独立性検定により、PSC と同時に出現する雲の出現高度は、9 ~ 11 km であることを示した。高緯度の冬季の平均的な圏界面高度は 8 ~ 9 km であり、この雲は成層圏に存在している可能性がある。これを検証するために、局所的に計算された圏界面高度からの相対高度に基づく解析を行った。結果、PSC と同時に出現する雲は、対流圏というよりも、対流圏界面付近及びそのやや上に存在することが明らかになった。以上の結果は、この雲を対流圏上層の雲ではなく、圏界面雲 (TropoPausal Cloud、以下、TPC) と呼ぶほうが適当であることを意味する。

PSC と TPC の同時出現のメカニズムを明らかにするために、それらが同時出現する際の力学場を調べたところ、対流圏界面付近に高気圧性 PV 偏差が存在する傾向があることが分かった。その PV 偏差は、数千 km の水平スケールを持ち、高度 15 km に及ぶ背の高い構造を持っていた。これはブロッキング高気圧の特徴と一致する。つまり、ブロッキング高気圧の上の低温によって、PSC と TPC が出現しやすい場になっていることが、それらが同時出現する上で重要であると考えられる。また、このブロッキング高気圧に伴う低温による、PSC 雲粒の組成への影響を調べた。ブロッキング高気圧の風下では、風上・直上に比べて、硝酸三水和物 (NAT) を多く含む雲が多いことが明らかになった。これは、先行

研究で指摘されている重力波に伴う急激な温度低下に伴う NAT の形成過程と、同様のプロセスが、より大きなスケールでブロッキング高気圧に伴って起こっていることを示唆している。ここまでで述べた、ブロッキング高気圧と PSC・TPC の関係は、南北両半球において成立することを確かめた。

2011 年の春季の北極で観測された、南極と同規模の成層圏オゾン減少の要因を考察するために、その年の 2 月の PSC の変動を解析した。他の年に比べて、PSC の出現頻度が非常に高い一方、PSC が TPC と同時に出現した割合が低いことが分かった。これは、2011 年 2 月については、ブロッキング高気圧の上の低温による PSC の増大の効果が相対的に小さかったことを示唆する。この年の PSC の出現頻度増大については、先行研究で別の要因が指摘されている。つまり、北西太平洋上のブロッキング高気圧と気候場として存在するトラフとが干渉し、成層圏に伝播するプラネタリー波が弱くなる。その結果、成層圏子午面循環が弱化し、極域がより低温となり、PSC 出現頻度が高くなったと考えられる。

次に、成層圏突然昇温 (Stratospheric Sudden Warming; 以下、SSW) 後の極域対流圏上層の雲の変動を、衛星ライダー観測、衛星掩蔽観測、再解析データを用いて、2009、2010、2012 年の SSW の事例に着目して調べた。SSW 後には、高度 7~12 km の雲の出現頻度の減少及び東西平均雲頂高度の低下が見られた。このような雲出現頻度の低下の際、対流圏界面付近での温度・静的安定度の上昇、及び対流圏界面高度の低下が観測された。このような変化は、SSW に伴う残差平均鉛直流が圏界面付近の高度で強化されるときに現れることを示した。さらに、近年提案された 3 次元残差平均流の理論や拡張ヒルベルト変換を用い、雲出現頻度と残差平均鉛直流の水平分布の関係を調べた。雲出現頻度が低下している領域と残差平均鉛直流は下降流が対応していることを示した。これは、

TEM 方程式系で見出された残差平均下降流と雲減少の関係が、水平方向で見た場合も成り立つことを示唆する。

また、雲出現頻度の低下や力学場の変動は、1 ヶ月以上持続する。この原因として、放射による緩和時間が下部成層圏で非常に長い (数 10 日以上) ことが考えられる。あるいは、SSW 後の対流圏の波活動の変化が寄与している可能性がある。しかしながら、SSW に伴う安定度の上昇が、対流圏擾乱へ影響を与えることも考慮する必要があり、それらを切り分けた研究が今後必要になる。

成層圏-対流圏の力学的結合についての多くの先行研究の中で、SSW は主要な役割を果たすと考えられている。今回の研究は、SSW 後の雲出現頻度の減少や雲頂高度の低下による放射収支への影響を通した、成層圏-対流圏の結合の可能性を示唆するものである。したがって、今回見出された雲変動に伴う放射収支への影響の定量化は、成層圏-対流圏結合のより深い理解のために、重要な課題であると考えられる。

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General introduction

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「Simultaneous occurrence of polar stratospheric clouds and upper-tropospheric clouds caused by blocking anticyclones in the Southern Hemisphere」平成 25 年 4 月 Atmospheric Chemistry and Physics 13 巻 7 号 3849-3864

Chapter 2

Simultaneous occurrence of PSCs and upper tropospheric clouds

In this chapter, the simultaneous occurrence of PSCs and upper tropospheric clouds are statistically examined using satellite observations and reanalysis data. It is shown that low temperature associated with blocking highs in the troposphere has a primary role in the simultaneous occurrence. The results strongly indicate the importance of the phases of atmospheric waves on the PSC occurrence. Note that the results on SH in this chapter have already been published as a peer-reviewed article (Kohma and Sato 2013).

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Chapter 3

Variability of upper tropospheric clouds during stratospheric sudden warming

In this chapter, the variability of upper tropospheric clouds during SSWs in NH is examined using two kinds of satellite observations and reanalysis data. It is found that the decrease in the cloud frequency in the upper troposphere and downward shift of mean cloud top heights are observed soon after SSWs. The results based on the TEM equation system and a recent theory of three-dimensional residual mean flow (Kinoshita and Sato 2013; Sato et al. 2013) are shown. The results suggest that the residual circulation (RC) driven by atmospheric waves affects the cloud frequency and the radiative budget in the upper troposphere.

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「Variability of upper tropospheric clouds during stratospheric sudden warming」Journal of Geophysical Research に投稿予定

Chapter 4

Summary and concluding remarks

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