Cloud Formation and Fractionation of Stable Isotope of Water within Artificial Cloud Experimental System (ACES)

***Yasushi Fujiyoshi [1], Sou Nakajima [2], Sadamu Yamagata [3], Toshio Harimaya[4], Tadashi Yamada[5], Ichiro Matsui[6], Nobuo Sugimoto[6] and Atsushi Shimizu[6]**
(1: ILTS, Hokkaido Univ./FRCGC, 2: Graduate School of Environmental Science, Hokkaido Univ., 3: Graduate School of Engineering., Hokkaido Univ., 4: Graduate School of Science, Hokkaido Univ., 5: Faculty of Sci. and Tech., Chuo Univ., and 6: National Institute for Enviromental Studies)
*** Inst. Low Temp. Sci., Hokkaido University, Japan, 060-0819, Sapporo,Japan.**
e-mail: fujiyo@lowtem.hokudai.ac.jp

Abstract

We invstigated cloud physics and cloud chemistry by using an artificial cloud experimental system (ACES). The system is made use of the vertical mine shaft with a quasi-real scale of natural clouds. The vertical shaft is 430 m in length and 2.5m x 5m in cross section. We can change the number density and chemical composition of CCN, and the updraft velocity (0.5 - 2.0 m/s). Many kinds of insturments were deployed both at the bottom and top of the shaft. Especially, we measured veritcal profiles of air temperature every 5 m or 10 m interval to detect the supersaturation layer near the cloud base. We also measured stable isotope of water vapor at the bottom of the shaft and cloud (condensed) water at several levels of the shaft. Since ACES is the quasi-closed system, we were firstly able to study the validity of the Rayleigh condensation (distillation) model.

Keyword:cloud physics, stable isotope of water, Rayleigh condensatin model

1. Introduction

Study of clouds becomes important especially in recent years, since they play an essential role in global climate systems through their interaction with shortwave and longwave radiation (e.g., Wielicki et al., 1995) as well as rain/snow formation. Also the acid rain, fog and cloud are quite serious problems of the earth environment (e.g., Hobbs, 1993). There are many and complex physical and chemical processes in clouds (e.g., Pruppacher and Klett, 1978). We can make laboratory experiment on some elemental processes, and numerically simulate the phenomena in clouds combining these elemental processes. However, such kinds of numerical simulations would not succeed in simulating natural phenomena and lead to misunderstanding of nature, if we do not take account of the interactions between these elemental processes. Therefore, we must check the validity or applicability of pure theoretical models and/or parameterized cloud schemes.

Many direct and field measurements of physical, chemical and radiative properties of clouds have been done both on the ground surface and in the air. The "CLEOPATRA" CLoud OberPfaffenhofen And TRAnsport (Meischner et al., 1993) was one of these field experiments. However, it is impossible to measure the same clouds repeatedly under the same conditions, because clouds grow and dissipate in a short period of time. Further, it is questionable whether the measured values are representative ones of a cloud or not, owing to its inhomogeneity both in space and time. Therefore, we need a quasi-real scale artificial cloud which is formed in the adiabatically ascending air and has reproducible properties.

On August 1989, we noticed that a quasi-real scale (several hundreds meter) cloud is formed in a long ventilation shaft of a mine below the ground. Then we deployed some instruments in the vertical shaft to study micro-physical and chemical processes in the cloud. From March, 1992 to August 1993, we had made use of a cylindrical shaft (1st shaft) with 5.5 m in diameter and 700 m in length located at Kamisunagawa-cho, Hokkaido, Japan. After the 1st shaft had to be closed forever on February 1994, we are making use of a new shaft (2nd shaft) with 2.75 m x 5 m in cross section and 430 m in depth located at Kamaishi, Iwate Prefecture.

The cloud depth, liquid water content and integrated liquid water content are small in the artificial cloud. However, the detailed study of thin clouds is very important, since shortwave cloud albedo increases very rapidly with increasing integrated liquid water content in the region below 100 g m^{-2} (Stephens, 1978). The number density of cloud droplets strongly depends on that of CCN when the updraft velocity is less than a few meters.

We reported some results of the experiments in several papers (Yamada et al. 1995; Yamagata et al., 1998; Harimay et al., 1998; Yamagata, 2003; Yamagata et al. 2004). In this paper we will discuss the veritcal profiles of air temperature measured every 5 m or 10 m interval to detect the stable layer and supersaturation near the cloud base.

The stable isotopic ratios of meteoric water (HDO/H_2O and $H_2{}^{18}O/H_2{}^{16}O$) has been used as indicators of past climate and source of water vapor (Friedman et al., 1964; Dansgaard, 1964; Dansgarrd et al., 1982; Jouzel et al., 1987). Since fractionation occurs during phase change, condensation of vapor as an air parcel cools progressively lowers the heavy isotope ratios of the remaining vapor and the condensate that forms from it (Rayleigh distillation/condensationprocess). So far, however, the Raylegih distillation processs has not proven, yet.

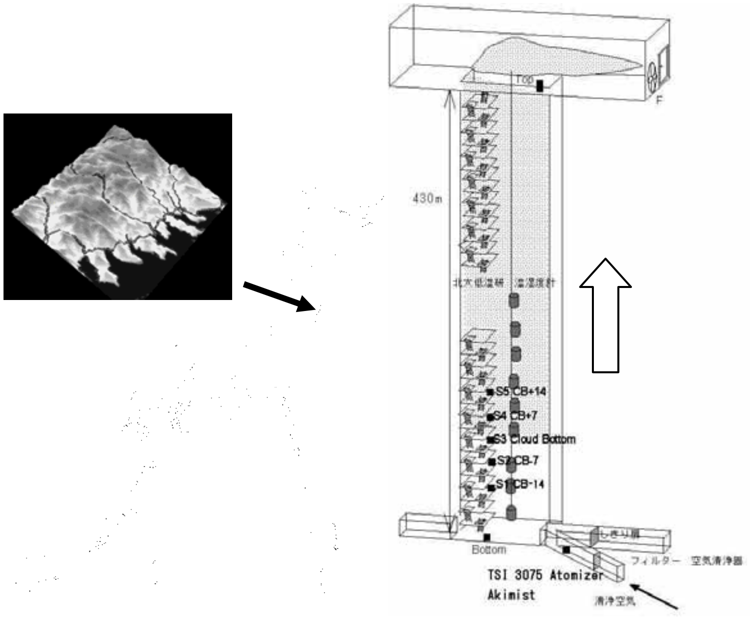

Fig. 1 The place and schematic outlook of ACES. (Yamagata, 2003)

2. Outline of the experimental system

ACES has four unique features: (1) A quasi-real scale cloud is formed in the adiabatically ascending air. (2) Processes included in this artificial cloud are more complicated than those of laboratory experiments, but the experimental conditions can be controlled. (3) Since this system is nearly one-dimensional and keeps nearly steady state, we can compare the experimental results with theoretical works on the small number of assumptions. (4) In situ measurements are possible in the cloud.

Figure 1 shows the outlook of the experimental system of the 2nd shaft. Two big fans set at the top of the shaft suck the air and causes updraft ranging from 0.5 to 2 m s^{-1} in the shaft. We measured changes with time of temperature and relative humidity of air at the bottom of the 1st shaft from April to August, 1992. Both temperature and relative humidity increased with time from 21.5 to 23.8 ℃ and from 51.4 to 73.8 % (Yamada et al., 1995). Therefore, it is expected that a cloud would be thicker in summer than in winter. As these changes with time were small, 0.015 ℃ day^{-1} and 0.15 % day^{-1}, we can assume that background temperature and relative humidity were constant during the measurements. Such surprizingly steady state is one of the unique and important features of ACES.

We hanged thermometers from the top of the shaft every 5 or 10 m interval. Under moist adiabatic conditon, 5 m interval causes only 0.03 ℃ difference. We sampled water vapor by using cold trap method at the bottom, and collected cloud (condensed) water at several levels and at the top of the shaft. The δO^{18} and δD of collected water were measured by using a mass-spectormeter of our institute.

Size distribution of aerosols were measured continuously both at the bottom and top, and that of cloud droplets was also measured by using PMS-probe at the top of the shaft. In 2003, we deployed a LIDAR (National Inst. for Environmental Studies) at the bottom to study the growth of aerosol near the cloud base. To change the number density of CCN, small droplets of aqueous solution of sodium chloride and ammonium sulfate were sprayed at the bottom (Yamagata et al., 2004).

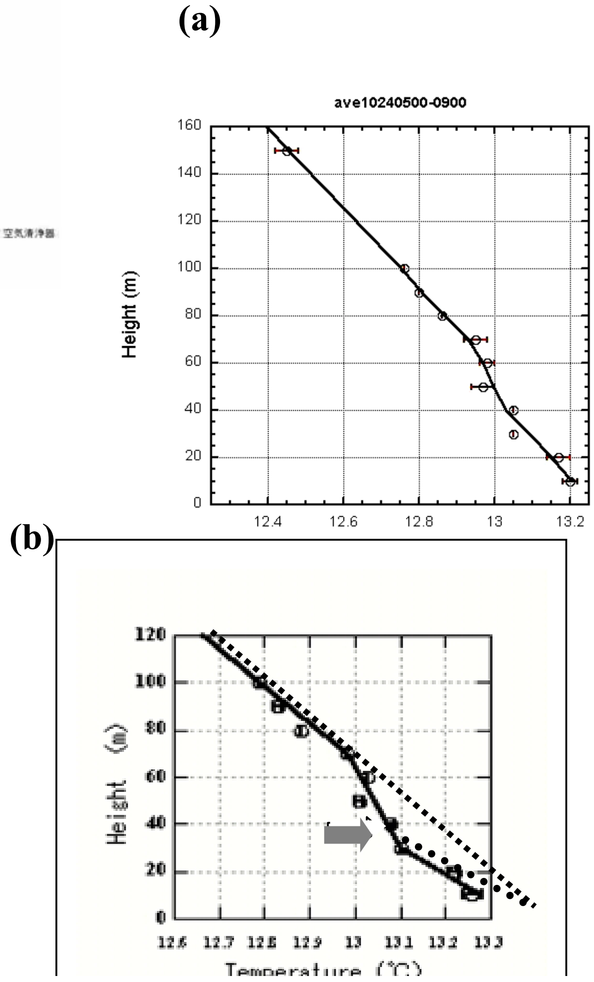

Fig. 2 Examples of observed vertical profiles of air temperature in the shaft.

3. Vertical profiles of air temperature

Theoretically, maximum supersaturation near the cloud base depends on chemical composition and the size distribution of CCN and ascending velocity. Therefore, initial size distribution of cloud droplets, optical thickness and precipitation efficiency of the cloud are strongly affected by the maximum supersaturation. However, the reliability of in situ measurements of the supersaturation is very poor as mentioned later. Here, we discuss the aerosol effect on vertical profiles of air temperatures to find out the maximum supersaturation layer that should be formed near the cloud base. Preliminary caluculation shows that the temperature lapse rate is dry adiabatic below the maximum super saturation level and moist adiabatic above it. Just above the maximum supersaturation level, condensation of water vapor on CCN rapidly occurrs, that is, a large amount of latent heat is released. Therefore, small value of temperature lapse rate should be found near the level of maximum super saturation.

Figure 2 shows that the observed lapse rate was close to dry-adiabatic one below 40 m and moist-adiabatic one above 70 m. In the meantime, the temperature lapse rate is clearly different in the layer from 40〜70 m, where the temperature lapse rate was much smaller than moist-adiabatic lapse rate. Qualitatively, the range in which the moist-adiabatic lapse rate line crosses with dry adiabatic lapse rate line of the lower layer is a supersaturated layer, and the maximum supersaturation exists in which the temperature difference is maximum (see an arrow in Fig. 2b).

Quite high sensitivity of thermometers and the stability of air temperature of the environmental atmosphere is indispensable to detect the maximum supersaturation (0.1〜0.05 C). We cannot expect such stability to in situ measurements.

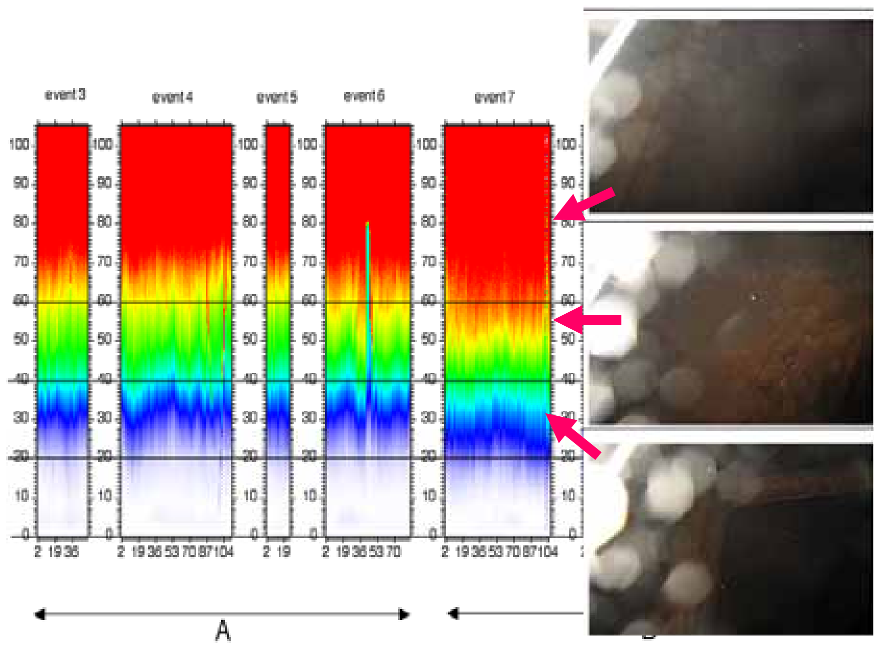

Fig. 3 Time series of vertical profiles of the extinction coefficient (λ=532 nm) and pictures of visibility in the shaft taken by a camera.

4. Detection of sub-cloud layer by LIDAR

LIDAR can measure the fine structure of sub-cloud layer, where CCN change from dry to wet aerosols. As shown in Fig. 3, the vertical profile of the extinction coefficent changed a little depending on updraft velocity, chemical composition and number density of CCN. However, these 5 cases show common featrues.

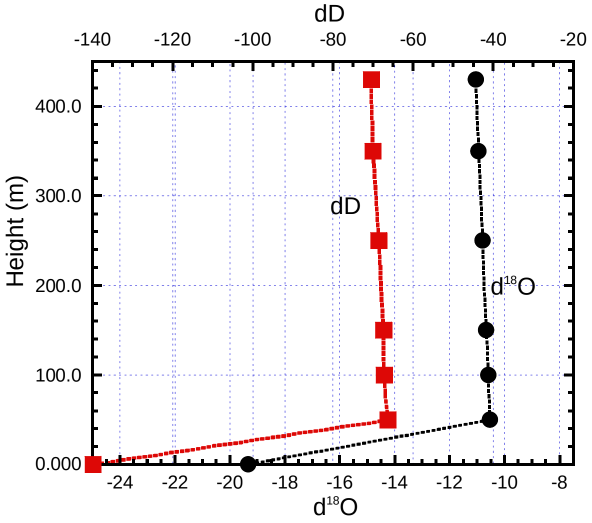

Fig. 4 Vertical profiles of $\delta^{18}O$ and δD of water vapor and cloud water

(1) Extinciton coefficient is small from the bottom to 20 m level, indicating the dry state of aerosol.

(2) Extinction coefficient increases rapidly in the layer between 20 m and 60 m from the bottom, indicating the condensational growth of aerosol.

(3) Extinction coeficient is quite large above 60 m from the bottom, indicating the formation of cloud droplets.

The pictures taken by a CCD camera (right panel of Fig. 3) support the explanation of LIDAR data. The results shown above are also consistent with those of vertical profiles of air temperature.

5. $\delta^{18}O$ and δD of water vapor and cloud water

Stable isotope of water is very useful tool to study the water cycle. Fractionation during phase change is the basic process. The accuracy of Ralyeigh condensation model has been tried to demonstrate by a few researchers (Gedzelman and Lawrence 1982; Gedzelman et al. 1989). However, their studies were made for snow sotrms, that is, non-closed system. We measured stable isotope of water vapor at the bottom and cloud (condensed) water sampled at several levels of the shaft. Since ACES is the quasi-closed system, we were firstly able to study the validity of the Rayleigh condensation (distillation) model.

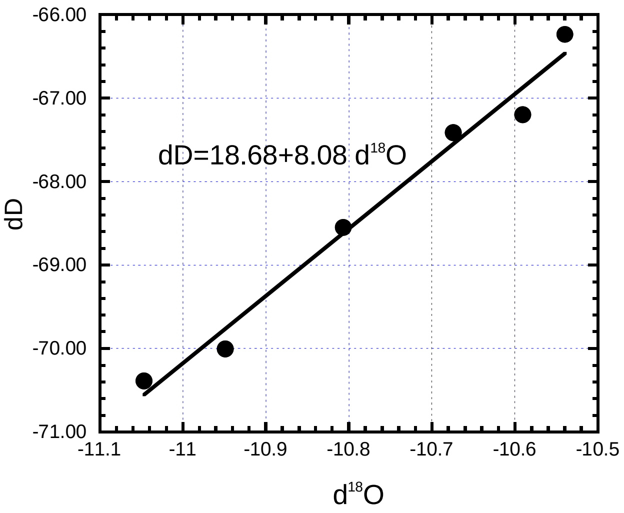

Fig. 5 Relationship between δ^{18}O and δD of cloud water.

Figure 4 shows the vertical profiles of δ^{18}O and δD of water vapor at the bottom and cloud water sampled at 50m, 100m, 150m, 250m, 350m and 430m (top). As is expected, δ^{18}O and δD of cloud water are much larger than those of water vapor at the bottom, and decrease with altitude. Since cloud droplets can grow only when the relative humidity is higher than 100 %, nonequilibrium condensation may affect the isotopic ratio of cloud water. The relation beween δ^{18}O and δD can be used to assess the role of nonequilibrium procesees. As shown in Fig. 5, $\delta D/\delta^{18}O$ slope is almost the same with that of the meteoric water line ($\delta D=7.97\delta^{18}O + 8.6$), and that of equilibrium condensation.

We are trying to simulate the vertical profiles of δ^{18}O and δD of water vapor and cloud water. We will try to measure these values just below, within and just above the maximum supersaturation layer, where non-equilibrium effect is the largest.

5. Concluding remarks

All the data observed are both micro-physically and chemically are consistent with each other, and clearly show the aerosol effect on vertical profiles of air temperature and supersaturation. All these data indicate that ACES is a good simulator of natural clouds and has the capability of studying the complex processes in natural clouds.

Acknowledgements: The authors are grateful to Dr. Takeshi Nakatsuka, ILTS Hokkaido Univ., for analysis of stable isotope of water. We also express our sincere thanks to Kamaishi Kozan Co. Ltd. for providing their facilities used for this experiment. Finally we wish to acknowledge the assistance provided by many students of Hokkaido University and Chuo Univeristy.

References

Dansgarrd, W., 1964: Stable isotopes in precipitation. Tellus, 16, 436-468.

Dansgaard, W., H. B. Clausen, N. Gundestrup, C. U. Hammer, S. J. Johonson, P. M. Kristindottir, and N. Reeh, 1982: A nes Greenland dep ice core, Science, 218, 1273-1277.

Friedman, I., A. C. Redfield, B. Schoen, and J. Harris, 1964: The variation of the deuterium content of natural waters in the hydrologic cycle. Rev. Geophys., 2, 177-224.

Gedzelman, S. D., J. M. Rosenbaum and J. R. Lawrence, 1989: The megalopolitan snowstorm of 11-12 February, 1983: Isotopic composition of the snow. J. Atmos. Sci., 46, 1637-1649.

Gedzelman, S. D. and J. R. Lawrence, 1982: The isotopic composition of cylonic precipitation. J. Appl. meteor., 21, 1385-1404.

Harimaya, T., S. Sasaki, T. Yamada, Y. Fujiyoshi, M. Inage, 1998: Construction and cloud physical properties of the Artificial Cloud Experimental System using a long vertical mine shaft. Geophy. Bull. Hokkaido Univ., 61, 23-34.

Hobbs, P. V., 1993: Aerosol-cloud interactions. International Geophys. Ser., 54, Academic Press Inc., 233pp.

Jouzel, J., C. Lourius, J. R> Petit, C. Genthon, N. I. Barkov, V. M. Kotkyakov, and V. M. Petrov, 1987: Vostok ice core: Acontinuous isotopic temperature record over the last climatic cycle (160,000 years). Nature, 329, 403-408.

Meischner, P. F., M. Hagen, T. Hauf, D. Heimann, H. Holler, U. Schumann, W. Jaeschke, W. Mauser and H. R. Pruppacher, 1993: The field project CLEOPATRA, May-July 1992 in southern Germany. Bull. Amer. Meteor. Soc., 74, Nr. 3, 401-412.

Pruppacher, H. R. and J. D. Klett, 1978: Microphysics of clouds and precipitation. D. Reidel Publishing Company, 714pp.

Qian, G. W., H. Tanaka, M. Yamato and Y. Ishizaka, 1991: Multiple thin film method for simultaneous detection of sulfate and nitrate ions in individual particles and its application to atmospheric aerosols. J. Meteor. Soc. Japan, 69, 629-640.

Stephens, G. L., 1978: Radiation profiles in extended water clouds. II: Parameterization scheme. J. Atmos. Sci., 35, 2101-2123.

Wielicki, B. A., R. D. Cess, M. D. King, D. A. Randall, and E. F. Harrison, 1995: Mission to planet earth: Role of clouds and radiation in climate. Bull. Amer. Meteor. Soc., 76, 2125-2153.

Yamada, T., T. Hibino, G. Fukawa, M. Matsuura, Y. Fujiyoshi, T. Harimaya, M. Inage, and M. Nakatsugawa, 1995: Prototype experiment of cloud physics using the long vertical shaft in a mine. J. Hydraulic, Coastal and Environmental Engineering, Japan Society of Civil Engineers, 509/II-30, 1-13.

Yamagata, S., S. Baba, N. Murao, S. Ohta, T. Fukuyama, M. Utiyama, T. Yamada, Y. Fujiyoshi, T. Harimaya, and M. Inage, 1998: Real scale experiment of sulfate dioxide dissolution into cloud droplets generated in Artificial Cloud Experimental System (ACES). J. Global Envi. Engineer., 4, 53-63.

Yamagata, S., 2003: Artificial cloud experiment in an vertical shaft in a mine. J. Aerosol Res., 18(4), 266-270.

Yamagata, S., T. Kuroda, T. Zaiman, N. Murao, S. Ohta, Y. Fujiyoshi, T. Harimaya, T. Yamada, K. Izumi, T. Fukuyama, and M. Utiyama, 2004: Mineral particles in cloud droplets produced in an Artificial Cloud Experimental system (ACES). Aerosol Sci. and Tech., 38, 293-299.