36469

National Library of Canada | Bibliothèque nationale du Canada

CANADIAN THESES ON MICROFICHE | ***THÈSES CANADIENNES SUR MICROFICHE***

NAME OF AUTHOR/*NOM DE L'AUTEUR* [illegible]

TITLE OF THESIS/*TITRE DE LA THÈSE* [illegible]

[illegible] Samples of [illegible] and

[illegible] from Alberta.

UNIVERSITY/*UNIVERSITÉ* University of Alberta

DEGREE FOR WHICH THESIS WAS PRESENTED/ *GRADE POUR LEQUEL CETTE THÈSE FUT PRÉSENTÉE* M.Sc. Meteorology

YEAR THIS DEGREE CONFERRED/*ANNÉE D'OBTENTION DE CE GRADE* 1978

NAME OF SUPERVISOR/*NOM DU DIRECTEUR DE THÈSE* Dr. R. B. Charlton

Permission is hereby granted to the NATIONAL LIBRARY OF CANADA to microfilm this thesis and to lend or sell copies of the film.

The author reserves other publication rights, and neither the thesis nor extensive extracts from it may be printed or otherwise reproduced without the author's written permission.

L'autorisation est, par la présente, accordée à la BIBLIOTHÈQUE NATIONALE DU CANADA de microfilmer cette thèse et de prêter ou de vendre des exemplaires du film.

L'auteur se réserve les autres droits de publication; ni la thèse ni de longs extraits de celle-ci ne doivent être imprimés ou autrement reproduits sans l'autorisation écrite de l'auteur.

DATED/*DATÉ* April 20, 1978 SIGNED/*SIGNÉ*

PERMANENT ADDRESS/*RÉSIDENCE FIXE* 6808 - 132 Ave

EDMONTON, ALBERTA

T6K 1R2

NL-91 (3-74)

National Library of Canada

Cataloguing Branch
Canadian Theses Division

Ottawa, Canada
K1A 0N4

NOTICE

The quality of this microfiche is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us a poor photocopy.

Previously copyrighted materials (journal articles, published tests, etc.) are not filmed.

Reproduction in full or in part of this film is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30. Please read the authorization forms which accompany this thesis.

THIS DISSERTATION
HAS BEEN MICROFILMED
EXACTLY AS RECEIVED

Bibliothèque nationale du Canada

Direction du catalogage
Division des thèses canadiennes

AVIS

La qualité de cette microfiche dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de mauvaise qualité.

Les documents qui font déjà l'objet d'un droit d'auteur (articles de revue, examens publiés, etc.) ne sont pas microfilmés.

La reproduction, même partielle, de ce microfilm est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30. Veuillez prendre connaissance des formules d'autorisation qui accompagnent cette thèse.

LA THÈSE A ÉTÉ
MICROFILMÉE TELLE QUE
NOUS L'AVONS REÇUE

NL-339 (3/77)

THE UNIVERSITY OF ALBERTA

INTERPRETING THE OXYGEN-18/OXYGEN-16 VARIATIONS IN SOME SAMPLES OF VAPOUR, RAIN, HAIL AND SNOW FROM ALBERTA

by

HARBHAJAN SINGH SANDHU

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE

IN

METEOROLOGY

DEPARTMENT OF GEOGRAPHY

EDMONTON, ALBERTA

SPRING, 1978

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled "Interpreting the Oxygen-18/Oxygen-16 Variations in Some Samples of Vapour, Rain, Hail and Snow from Alberta", submitted by H. S. Sandhu in partial fulfilment of the requirements for the degree of Master of Science in Meteorology.

Robert Charlton
Supervisor

Karlis Muehlenbachs

Keith D. Hage

Date April 19, 1978

ABSTRACT

During the past two decades, naturally occurring stable isotopes of oxygen and hydrogen have been used in different laboratories to study the precipitation formation process. Although this technique has been known for several decades relatively little progress has resulted due to field, laboratory and theoretical difficulties. In the case of hail studies, field sampling of precipitation and water vapour is hazardous and difficult to control. Laboratory analyses require specialized sample preparation techniques and sophisticated mass spectrometers.

A program of sampling vapour and precipitation in Alberta was undertaken during the springs and summers of 1974, 1975 and 1976 in order to understand and model precipitation processes, typical of this region; with stable isotopes. A simple convective cloud model has been considered to interpret the observations. The temperatures of formation of hail and graupel were calculated employing this model. Results show that small hail and graupel appear to collect most of their mass in the warm regions of the cloud.

Isotopic values obtained in the present study have been compared with established relations between δD, $\delta^{18}O$ and mean temperatures. Satisfactory agreements are obtained in most cases. Suggestions for further work have been made.

ACKNOWLEDGEMENTS

I wish to express my gratitude to Dr. R. B. Charlton for his suggestions, encouragement and stimulating discussions during the course of this study. I am also thankful to Drs. E. P. Lozowski and K. D. Hage for encouraging me to learn the subject of meteorology.

Special thanks are due to Dr. J. Gray and his associates, Department of Physics, for their help in carrying out the mass spectrometric analyses of samples.

I wish to express my appreciation to Mr. W. Horton for his enthusiastic approach to field sampling, Mr. D. Ellis for his help with data analysis and Drs. S. B. Smith and W. R. MacDonald of the Alberta Department of the Environment for encouraging me to complete this investigation.

Financial support of this research project by the National Research Council of Canada and the technical support from the Alberta Weather Modification Board is gratefully acknowledged.

Finally, and most importantly, I wish to thank my wife, Surjit, and three children for their patience and support.

TABLE OF CONTENTS

CHAPTER Page

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 General

Most of our usable water is released in the form of precipitation from the atmosphere. For over a century scientists have attempted to understand precipitation and other associated phenomena. It is only during the last three decades that the broad subject of cloud physics has become better understood mainly because of technical developments in the probing instrumentation. A detailed review of this subject is beyond the scope of this study. However, excellent books on cloud physics by Byers (1965), Fletcher (1969), Mason (1971, 1975), and Rogers (1976) are available.

1.2 Isotopic Content of Water and Its Designation

Atoms of many elements are found in nature having different atomic weights. Those atoms which have the same atomic number but different atomic weight are called isotopes. The chemical properties of isotopes of a given element are almost identical because the properties depend mainly upon the orbital electrons. The isotopy of elements influences physical processes like diffusion, absorption, evaporation and condensation, the last two being of special interest to the present study.

A water molecule consists of two hydrogen atoms and one oxygen atom. Hydrogen has two stable isotopes ^1H (Hydrogen) and ^2H (Deuterium or D), whereas oxygen has three (^{16}O, ^{17}O and ^{18}O). In the case of water, $HD^{16}O$ and $H_2{}^{18}O$ are the most abundant after $H_2{}^{16}O$. Another isotope of hydrogen, ^3H (Tritium or T) which is unstable is worthy of mention here. In the environment tritium comes mainly from thermonuclear explosions. Production of T by cosmic radiation is of minor significance. The exchange reactions between T and light water molecules give rise to tritiated water (HTO). These have been used as tracers to study the natural water systems (International Atomic Energy Agency, 1969, 1970, 1971).

The abundance of $H_2{}^{18}O$ in natural waters is 2000 parts per million. The absolute concentrations of isotopic species are difficult to measure accurately. However, the difference in the ^{18}O content of two samples can be determined with high precision using mass spectrometric techniques. The measurements are reported giving delta values (δ) defined by the expression

$$\delta(^0/_{00}) = \left[(R_{sample}/R_{standard}) - 1\right] \times 10^3 \text{ (parts per thousand)}, \quad (1)$$

where R_{sample} and $R_{standard}$ are the $^{18}O/^{16}O$ or D/H atomic ratios in the sample and standard, respectively. The reference standard employed is SMOW (Standard Mean Ocean Water) as proposed by Craig (1961).

When a sample δ value has been measured in terms of local or working standard, its value on the SMOW scale can be obtained from the following relationship, provided that $\delta_{standard}$ is known relative to SMOW.

$$\delta^{sample}_{SMOW} = \delta^{sample}_{standard} + \delta^{standard}_{SMOW} + \delta^{sample}_{standard}\ \delta^{standard}_{SMOW} \times 10^{-3}\ {}^{0}/_{00} \quad (2)$$

1.3 Isotopes in the Hydrological Cycle

Isotopic fractionation of water, i.e., changes in the fraction of $H_2{}^{18}O$ or $HD^{16}O$ in nature can be attributed to a number of physical, chemical and biological processes. In the atmosphere, the following processes lead to changes in the abundance of isotopes (fractionation):

1. Evaporation of vapour from water body surfaces and land and evapotranspiration from vegetation.
2. Condensation of vapour during cloud formation.
3. Isotopic exchange between vapour and its environment.
4. Evaporation from falling precipitation.

Comprehensive discussions of this topic have been given by Dansgaard (1964), Craig and Gordon (1965) and Dincer (1968). The main results of the previous studies can be summarized as follows:

1. The isotopic composition of ocean water is nearly constant with concentrations of 997680:2000:320 ppm (parts per million) for $H_2{}^{16}O$, $H_2{}^{18}O$ and $HD^{16}O$, respectively. For instance

$R_{SMOW} = 1.9934 \times 10^{-3}$ by convention for $H_2{}^{18}O - H_2{}^{16}O$ (Craig, 1961).

2. The isotopic species are fractionated during evaporation and condensation processes because of differences in transport rates to and from water body surfaces, land and vegetation.

3. When liquid and vapour are in equilibrium the ratio α of the atomic ratio of $H_2{}^{18}O$ to $H_2{}^{16}O$ in liquid (R_L) to that in the vapour (R_v) is dependent on temperature (T) only. This ratio of the abundance of the heavy isotope in the liquid relative to that in the vapour is proportional to the ratio of the saturation vapour pressure of the common isotope $(e_{H_2{}^{16}O})$ to that of the heavy isotope $(e_{H_2{}^{18}O})$ in accordance with Raoult's law. This ratio is called the fractionation factor (α) and it can be written as:

$$\alpha = R_L/R_v = e_{H_2{}^{16}O}/e_{H_2{}^{18}O} .$$

The fractionation factor decreases with increasing temperature.

4. A linear correlation between the mean annual surface temperature $T(^{\circ}C)$ and $\delta^{18}O$ values was derived by Dansgaard (1964) from available data for high latitude non-continental atmospheric precipitation. This has the form

$$\delta^{18}O = 0.69\,T - 13.6\ (^{0}/_{00}) . \qquad (3)$$

It was also concluded that heavy isotope content of precipitation showed a minimum in winter and a maximum in summer.

5. On the basis of 400 samples of water from streams, lakes and precipitation, Craig (1961) established the following linear relation between δD and $\delta^{18}O$:

$$\delta D = 8\,\delta^{18}O + 10 \tag{4}$$

The value of slope and the constant depends upon the air humidity, kinetic processes during evaporation, and isotope exchange processes. The "universal" nature of this approximate equation has been confirmed by more recent studies (Rychkov and Vetshteyn, 1976; Hage, Gray and Linton, 1975; Miyake, Matsubaya and Nishihara, 1968).

1.4 Hail Studies

The first application of isotopic technique to obtain information on the growth environment of a hailstone was demonstrated by Facy, Merlivat, Nief and Roth (1963). These authors determined the D/H ratio of the successive layers of a hailstone and used these values, along with the knowledge of the vertical structure of the atmosphere during the shower, to trace its life history. They assumed that the isotopic content of each layer of the hailstone represented that of the supercooled cloud droplets which were accreted during its formation. During condensation, isotopic fractionation leads to enrichment of the liquid phase in heavy isotopic molecules, HDO and $H_2{}^{18}O$. As the condensation proceeds and the air parcel rises the remaining vapour becomes progressively depleted in the heavy isotopic species. Thus the isotopic analysis provides a measure of temperature and consequently the height at which that layer was formed.

Since then a number of articles on the isotopic analysis of hailstones from different regions of the globe have been published (Majzoube, Nief and Roth, 1968; Baily, Hulston, Macklin and Stewart, 1969; Macklin, Merlivat and Stevenson, 1970; Knight, Ehhalt, Roper and Knight, 1975; Jouzel, Merlivat and Roth, 1975; Macklin, Knight, Moore, Knight, Pollock, Carras and Thwaites, 1977; Ross, Schooling and Vogel, 1977). None of these studies includes measurement of isotopic ratio of the vapour feeding the cloud.

1.5 Modelling of Precipitation

It is well known that a cloud is formed by adiabatic cooling of a saturated air parcel during ascent. The major process in the formation of rain, hail or snow involves the capture of cloud droplets. The isotope content in the precipitation depends upon the isotope content in the cloud droplets. When this capture involves the instantaneous freezing of cloud droplets, such as during graupel (snow pellet) formation, the δ value of the cloud droplets is "frozen" into the particle for future field sampling. Liquid precipitation on the other hand tends to change its isotopic value during subsequent growth in the cloud and during evaporation below the cloud base. Two types of models for the cooling processes, namely closed and open models, under equilibrium and non-equilibrium conditions, have been described in the literature to explain the isotopic content of cloud and vapour.

In a closed model, cloud droplets and vapour are not separated during cooling, i.e., the cloud droplets are not precipitated out. In the case of an open model, some of the cloud droplets are precipitated out of the system. This causes the remaining vapour to become more quickly depleted in heavier isotopes than in the closed model.

Non-equilibrium models attempt to model processes in which the delta of vapour relative to the delta of the condensed water is not determined by the fractionation factor during evaporation or condensation. For instance, in Rayleigh distillation δ_{vapour} is determined by δ_{liquid} and the fractionation factor: therefore, δ_{vapour} is independent of the vapour which had previously evaporated.

Miyake, Matsubaya and Nishihara (1968) have studied the time variations of the isotopic content of precipitation of both warm frontal (continuous) and cold frontal precipitation (showers). With warm fronts the heavier isotope content in precipitation increases with time at a fixed point on the ground. In showers, however, no simple rule in isotopic variations with time is observed. This is because the delta value of precipitation is lower if it forms high in a cloud and higher with greater evaporation below the cloud base.

The latest attempt in modelling hailstone growth using isotopes is that of Jouzel, Merlivat and Roth (1975). They have analyzed and discussed variations in the isotopic content of hailstones on the basis of the model proposed by Chisholm (1970). According to this model, cloud is divided into two regions; an updraft core unaffected by entrainment phenomena and the boundary zone influenced by these phenomena. The relevance of the above models will be discussed further in a later chapter.

1.6 Objectives of the Study

This study was initiated with the following four objectives:

1. To obtain $H_2{}^{18}O/H_2{}^{16}O$ and HDO/H_2O ratios in vapour for continental air masses and relate this data to precipitation data on an hour to hour basis.
2. To interpret and explain isotope variations in vapour and precipitation in terms of simple cloud models of showers and thundershowers.
3. To use a simple cloud model to estimate the temperature at which snow pellets and small hailstones form since these particles are potential embryos for large hailstones.
4. To compare oxygen-18/oxygen-16 variations in various forms of precipitation from Alberta with published studies from other regions of the globe.

CHAPTER 2

EXPERIMENTAL PROCEDURES

2.1 Procedure for Collecting Water Vapour

Chapter 1 reviewed previous research on the isotopic content of precipitation from convective clouds. This study was designed to monitor the isotopic content of the water vapour feeding such clouds as well as the precipitation which is formed. To perform an adequate number of experiments it was frequently necessary to collect water vapour samples from a travelling van (enclosed light truck). Portability dictated the design of the vapour condenser. A forty kilogram block of dry ice was found to last for one week when stored in the van's freezer. This made extended trips possible during which vapour could be collected using dry ice as a coolant and to preserve hailstones.

Vapour was collected using standard condensers or Horibe traps made locally from glass tubing. Outer glass tubing (1.2 cm o.d.) was coiled around a center glass tube (5 cm o.d.) which had knobby restrictions to air flow to give the condenser an approximate total diameter and height of 8 and 30 cm, respectively. Air was sucked first into the broader center tube and then around the outer coil by connecting the condenser with polyethylene tubing to a twelve volt air mattress pump. During suction, the condenser was submerged in a dry ice-ethanol slush bath. The ideal temperature of such a slush bath is -70°C, but it was found that -55°C to -60°C was easier to maintain in the field. Slush bath temperatures were maintained and noted during field experiments. The pumping speed of the twelve volt air mattress pump was lowered by reducing the cross-terminal voltage to about four volts.

The equipment was mounted in the van during field experiments. The air intake was at the front of the van. It took between one and two hours to collect two to three milliliters of water-equivalent ice in the condenser. This amount of water was required for the oxygen isotope analysis. About one-half to one-quarter of a cubic meter of air passed through the condenser in the one to two hour sampling time. During the sampling time the ice would occasionally build up and reduce air flow at the point where the air left the large diameter center tube and entered the outer coil. At that time the pump was turned off, the condenser removed from the slush bath, and the bottom of the condenser was submerged in a tray of water to melt the ice blockage. The condensing experiment was then resumed. When enough ice was collected the condenser was removed from the slush bath. The air entrance and exits were plugged quite tightly with foam rubber, and the ice was allowed to melt and collect at the bottom of the condenser for a few hours so that it could be poured out into a bottle.

Experiments were performed in the laboratory to determine the influence of the rate of air flow and slush bath temperature on the isotope content of the sample and on the fraction of the water vapour condensed. The results of these tests were favourable with delta values generally within 0.5 parts per thousand and about 95 percent of the vapour was collected under typical conditions. These tests were mainly done in the third summer of sampling (1976) after previous experiments indicated that added confidence in the vapour collecting technique should be developed.

By the third summer of experiments (1976), it became evident that the isotopic content of near ground water vapour varied considerably during typical summer days due to varying ground wetness and daytime atmospheric mixing. To get instantaneous vapour samples, some large plastic bags of volume approaching one-half of a cubic meter were made up. Using these bags to store air samples, it was possible to reduce the vapour sampling time from one or two hours to a couple of seconds. In this way breezes were monitored as frequently as seven times as a thundershower approached. The bags were stored in the van and the vapour condensed by pumping the air out at a later time under condenser conditions similar to earlier "non-bag" experiments.

2.2 Procedure for Collecting Precipitation

During the spring of 1974 experiments were designed to collect graupel (snow pellets) from convective clouds on the same dates as water vapour samples were collected. Commercial size plastic garbage bags were held open for a minute or two to collect the snow pellets or rain which was falling. Sometimes mixed rain and small hail were collected. A small bottle was used to quickly dip the precipitation from the bottom of the sampling bag before significant evaporation could occur. Occasionally freshly fallen graupel was picked off the ground. Several samples were frequently taken from a single shower. A field trip to the mountains that spring resulted in snow also being sampled by the bag technique and by removal from the snow-pack. Most precipitation samples were about ten milliliters in volume.

With the coming of summer, snow pellets seldom reach the ground on the plains before melting or at least partly melting. Two techniques were devised to separate rain from the unmelted ice ~~pellets~~. The ice pellets were to be analyzed for isotope content for comparison to the vapour's isotope content so that one could estimate the cloud temperature at which they formed. The first technique for separating rain and hail used a box with sponge rubber in the bottom. When exposed to precipitation the rain water was soaked up by the sponge and the ice particles stayed on top. After bottling the ice particles the rain water was wrung out into another bottle. The second method of separating hail from rain had the precipitation coming through a funnel in the roof of the van after which the hail was deflected by a screen and the rain fell through the screen.

Hail was frequently picked off the ground and stored in the van's freezer for later analysis and bottling. Frozen hail samples were also available from the Alberta Hail Project (ALHAP) sampling program and from individuals who had stored hailstones in their freezer.

Sequential precipitation samples were frequently taken to get minute by minute changes during the showers. Bag samples were generally not timed accurately enough to get precipitation rates but standard ALHAP beakers were often used to collect timed precipitation samples so that precipitation rates could be calculated.

2.3 Conduct of Field Experiments

During the first spring (1974) two hour vapour samples were collected prior to the onset of graupel showers. These showers were sought out using a car and the vapour samples were taken at the University of Alberta. Frequent weather notes were made during these experiments. The only field measurements besides precipitation were wet and dry bulb temperatures. These experiments were conducted to try to measure the temperature of graupel formation by using the isotopic content of the vapour and the graupel particles.

Late in May of 1974 a trip to the mountains was made to test the newly-equipped van and to develop sampling techniques for all precipitation types. These experiments are discussed in the section on 1974 results.

During the summer of 1974 the weather radar situated at ALHAP's research site near Red Deer was used along with a two-way radio in the van to guide the experiments to sites of probable hailfall. Water vapour samples were taken during the morning and again on the way to shower activity. Vapour sampling was interrupted during showers since it would not be representative of air feeding the clouds. Frequent notes on paper and on tape recordings were taken during these "hail chases" as well as during the two hours of vapour sampling. All sampling was done by experienced meteorology students.

During the summer of 1975 emphasis was put on water vapour sampling and seeking out heavy rain and heavy mixed rain and hail showers because our 1974 experience indicated that the influence of evaporation on the isotopic content of rain water could be eliminated during very heavy precipitation. It was unfortunate that even using radar guidance, little success was achieved that summer in locating very heavy precipitation events. These experiments were based on the theory that when heavy rain and hail fell simultaneously, most of the rain was from melted hailstones. In this case the isotope content of the rain, small hail and vapour would tell whether the unmelted hailstone centers were formed at colder or warmer levels in the cloud than the rain which would come from melted outer layers of hailstones or melted small hailstones.

During 1975 the two hour samples of water vapour were showing considerable diurnal variations. This indicated a need for instantaneous vapour samples and a study of the variation of the isotope value of vapour during the approach of thundershowers.

The spring of 1976 was devoted to tests of the vapour sampling techniques under laboratory conditions.

The summer of 1976 was devoted to frequent sampling of water vapour through the bag sample technique as showers approached and to the seeking out of heavy shower events using the 1975 techniques.

The results of these three years of experiments are covered on a day-by-day basis and summarized in the third chapter of this study. It should be stressed again that extensive field notes were necessary to make sense out of these case studies. The objective of measuring the isotopic hydrology of individual thundershowers was always the prime objective of the observers.

2.4 Meteorological Data

Surface wet and dry bulb temperatures were measured in the field using a sling psychrometer. The meteorological data needed to calculate the isotope model in the next chapter are given in Appendix A. Some of the information contained in this Appendix was obtained either from the Atmospheric Environment Service of Environment Canada or from the Alberta Hail Project. Some important weather observations taken from field study notebooks are also given in Appendix A.

2.5 Oxygen Isotope Analyses Procedure

Water poses serious problems when introduced into the mass spectrometer ionization chamber for isotopic analyses. However, $^{18}O/^{16}O$ ratios of water samples can be obtained indirectly by analyzing carbon dioxide equilibrated with a given liquid sample. The following exchange reaction occurs:

$$H_2{}^{18}O \text{ (liquid)} + C^{16}O_2 \text{ (gas)} \rightleftarrows H_2{}^{16}O \text{ (liquid)} + C^{16}O^{18}O \text{ (gas)}. \quad (5)$$

For precise determinations, the amount of CO_2 used must be considered, particularly if its isotopic composition differs significantly from the sample. Linton (1972) has discussed the consequences of ignoring this correction under experimental conditions similar to those employed in the present study. For less precise measurements, it is not necessary to know the fractionation factor α, defined as

$$\alpha = \frac{(^{18}O/^{16}O)_{CO_2}}{(^{18}O/^{16}O)_{H_2O}} . \tag{6}$$

The fractionation factor is temperature dependent and decreases with increasing temperature. If water is the dominant component of the system, then

$$\delta^{18}O_{system} = \delta^{18}O_{water} . \tag{7}$$

Isotopic separation factor of CO_2-water system has recently been discussed by Horibe, Shegehore and Takakakuwa (1973).

2.6 Equilibration of Water Samples with Carbon Dioxide

The following procedure, developed by Epstein and Mayeda (1953), was used. It is also described by West (1972).

1. About 2-3 ml of water were pipetted into each of six 25 ml equilibration flasks. A drop of HNO_3 was added to help in establishing equilibration.
2. After closing, the flasks were attached to the vacuum line. Samples were frozen with liquid nitrogen and then the air was pumped out with a fore pump.
3. A thaw and freeze procedure was carried out for about 5 minutes in a dry ice-ethanol slush bath and at room temperature, and the air removed from the samples with a mercury

diffusion pump.

4. Commercially available CO_2 was introduced into the flasks, with the pressure ranging from 41-170 mm Hg (5.3-22.7 kPa). Flasks were closed tightly and then removed from the vacuum line.
5. Equilibration was carried out in a constant temperature bath maintained at 26°C. The flasks were left in the bath for 30-70 hours duration.
6. After equilibration, the flasks were again attached to the equilibration vacuum line and water samples frozen in a dry ice-ethanol slush bath.
7. Using a liquid nitrogen bath, CO_2 gas from each sample flask was then transferred through two slush baths to breakseals or screw-type flasks. In the present study, mainly breakseals were used to avoid leakage.
8. The breakseals were then sealed and labelled for mass spectrometric analyses.

2.7 Isotopic Data

Experimental work was carried out in the Physics Department, University of Alberta, using the equipment and facilities of Dr. J. Gray. The mass spectrometric procedure described by Coleman and Gray (1972) was followed for measuring $^{18}O/^{16}O$ ratios.

Measured $\delta^{18}O$ values relative to the local standard and with respect to SMOW are given in Appendix B along with the volume of sample and the pressure of CO_2 used for equilibration. Four δD values, reported in Table B-1 were determined by Dr. H.R. Krouse of the University of Calgary. Calculations of delta relative to SMOW were made using equation (2). No corrections have been applied for various pressures of CO_2 used in the equilibration of water samples.

CHAPTER 3

RESULTS AND DISCUSSION

3.1 Closed System in Equilibrium Model

An attempt is made to interpret the isotopic measurements employing this simple model. It is an adiabatic model of a convective cloud in which vapour is in isotopic equilibrium with the condensed water and none of the cloud water is precipitated out. Also, there is no mixing of the cloud parcel with the air surrounding the cloud.

The following relationships can be written in terms of N, the number of moles of various isotopic species in the closed equilibrium system.

$$N^{18}_{c} + N^{18}_{v} = N^{18}_{vo} \qquad (8)$$

$$N^{16}_{c} + N^{16}_{v} = N^{16}_{vo} \qquad (9)$$

$$\text{Fractionation factor } \alpha = \frac{N^{18}_{c}/N^{16}_{c}}{N^{18}_{v}/N^{16}_{c}} = \frac{R_{c}}{R_{v}} \qquad (10)$$

$$\text{Fraction condensed } F = \frac{N^{16}_{v}}{N^{16}_{vo}} \qquad (11)$$

$$\text{Initial isotopic ratio in Vapour } R_{vo} = \frac{N^{18}_{vo}}{N^{16}_{vo}} \qquad (12)$$

The subscripts c, v and vo refer to condensate, vapour and initial vapour, while the superscripts 18 and 16 denote $H_2{}^{18}O$ and $H_2{}^{16}O$ molecules, respectively. Rearrangement of the above equations with the elimination of N's leads to the following relationship.

$$R_c = \frac{R_{vo}}{(1/\alpha - 1)F + 1} \qquad (13)$$

Equation (13) gives the isotopic ratio of the condensed cloud water (R_c) in terms of the isotopic ratio of the water vapour (R_{vo}) entering the cloud base at the lifting condensation level (LCL). Both F and α are functions of cloud temperature and they can be calculated at various altitudes by means of a tephigram if the cloud base (LCL) temperature and pressure are known.

In terms of delta values, equation (13) can be approximated by:

$$\delta_c - \delta_{vo} = (10^3 + \delta_{vo})(\alpha - 1)F \qquad (14)$$

where δ_c is the delta value of the condensing water and δ_{vo} is the delta value of the vapour at cloud base. For the delta values obtained in our experiments, δ_{vo} can be approximated at -25 °/oo for use in the right hand side of equation (14). Furthermore, if α is written as

$$\alpha = 1 + \frac{x}{1000}, \tag{15}$$

then for $\alpha = 1.0135$ at -20°C, $x = 13.5$. Values of α used in this study are 1.0135, 1.0123, 1.0116, and 1.0101 for temperatures of -20, -10, 0, and +10°C, respectively (Dansgaard, 1964). Therefore, x varies from around 13.5 at -20°C to 10.1 at 10°C. These are normal cloud temperatures employed in the calculations. The δ values of the condensing cloud water δ_c can, therefore, be approximated at various temperature levels in the cloud by:

$$\delta_c = \delta_{vo} + 0.975\ Fx \tag{16}$$

From the values of x at various temperatures one finds that x increases by about 1.25 units per 10°C of cooling starting with $x \doteq 10.1$ at 10°C. A tephigram gives F as a function of cloud temperature. Calculating equation (16) for δ_c, one finds that δ_c falls off by 4.1, 2.8, and 2.0 $^{o}/oo$ for the first, second, and third ten degrees of cooling above the cloud base, provided that the cloud base temperature is around 0°C. If the cloud base temperature is 10°C (warm for Alberta) δ_c would fall off by about 2.7, 2.5, and 2.0 $^{o}/oo$ for the first, second and third 10°C of cooling above the cloud base. Snow pellets, and to some degree hailstones, form when cloud droplets with characteristic δ_c freeze by riming on their surface. This indicates the model's ability to estimate the cloud temperature at which a snow pellet formed by finding its δ value and δ_{vo} to ± 0.2 $^{o}/oo$. As indicated above, the accuracy of snow pellet formation temperatures calculated with this model is greater in a cloud with a cold base than a cloud with a warm base since δ_c falls more quickly with temperature in a cold-based cloud. This assumes that a snow pellet (graupel particle) or a small hailstone forms by freezing accreted supercooled water droplets which do not change their δ value when they freeze. It is also assumed that the snow pellets or small hailstones are able to maintain their δ_c value as they melt on descent from the freezing level.

Figure 1 summarizes schematically how the δ value of vapour and cloud water varies with altitude in this model. Arrows indicate how the δ values would vary if the cloud has a significant precipitation efficiency. In that case, the cloud water which is rich in $H_2{}^{18}O$ near the cloud base precipitates out, leaving lower values at higher altitudes. This precipitating model was called the Open System in Equilibrium by Miyake et al. (1968), and was also used by Facy et al. (1963). It has been compared to clouds caused by slow, warm frontal accent but it probably has some similarity to a cumulonimbus shower with high precipitation efficiencies as well. This model indicates that the δ values of the cloud droplets at a given altitude in the cloud should be lower as the precipitation efficiency increases.

In summary, Figure 1 shows that δ_c at cloud base will be about 10-14 $^{o}/oo$ (equal to x) higher than δ_v, and that δ_c will decrease by about 4, 3, 2 $^{o}/oo$, respectively, for each successive 10^{o}C of cooling in a convective cloud with a base temperature of 0^{o}C. δ_c will decrease somewhat less quickly with altitude in a cloud with a warmer base temperature.

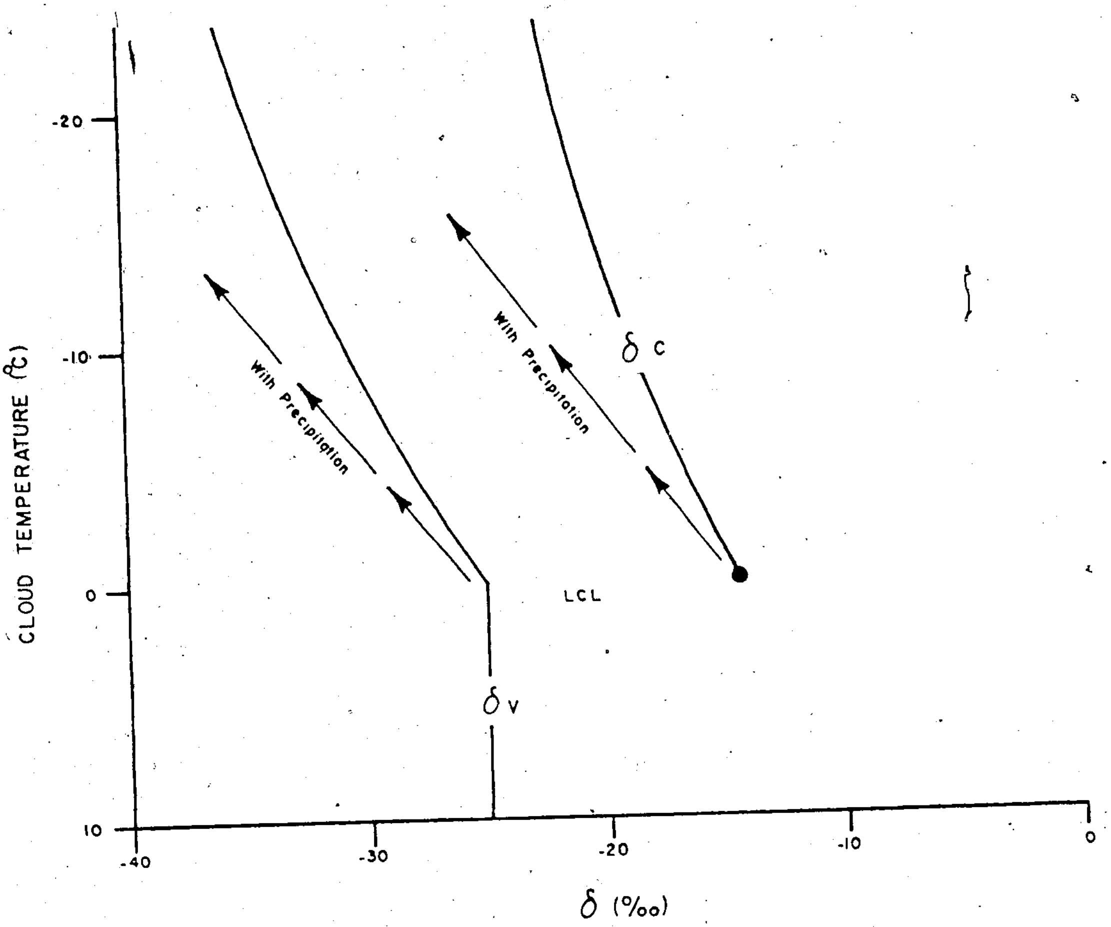

FIGURE 1: SAMPLE TEMPERATURE vs δ IN MODEL

An analogous study to that described above, for the fractionation of $HD^{16}O$ in a convective cloud could have been used to check the results of the $H_2{}^{18}O$ model. Unfortunately, at the time of these experiments, deuterium analysis facilities were not readily available on the University of Alberta campus. As mentioned in the previous chapter, four water samples were sent to the University of Calgary for analysis, and the results are discussed later. Both $HD^{16}O$ and $H_2{}^{18}O$ models could be used to calculate the cloud temperature at which snow pellets or hailstones formed. Reviews by Dansgaard (1964) and Craig and Gordon (1965) indicate that the difference between the precipitation formation temperatures calculated by these two models would be an indication of the non-equilibrium processes at work in the cloud and during melting and evaporation below the cloud base. Such a study would be a useful continuation of the work reported here, however, it would probably not successfully isolate the contribution of the various non-equilibrium effects.

3.2 Discussion of 1974 Results

The delta values of 1974 samples as well as some meteorological parameters are displayed in Figure 2. Some of these results have already been discussed (Charlton, Gray and Sandhu, 1975). The observations are discussed on an event basis emphasizing those situations when samples of both vapour and precipitation were collected.

MAY 15. Three samples of small hail (3 dots in the symbol for graupel or small hail), two samples of rain water and one of vapour were collected, all within 20 km of Edmonton. Arrows in Figure

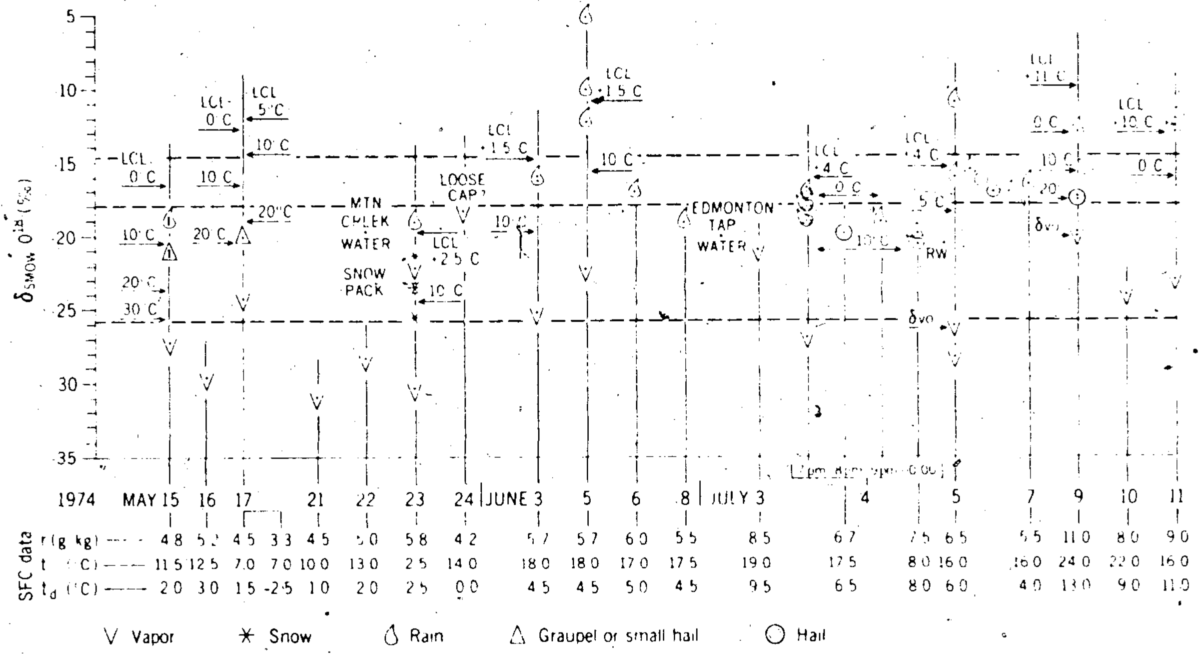

Figure 2. $H_2{}^{18}O$ in vapour and precipitation in 1974. The dashed lines represent average delta values of vapour, hail and rain for the 1974, 1975 and 1976 studies.

2 show temperatures of the cloud water at the corresponding δ values, calculated using equation (16), a tephigram, δ_{vo} and the temperature data given at the bottom of Figure 2. Comparing the δ values with various temperatures indicates that the small hail (≈5 mm in diameter) collected cloud droplets, on the average, at the -10°C level.

MAY 17. Calculation of the cloud temperature at which the graupel grew was made difficult by large fluctuations in surface dew point (2.5 to -2.5°C). This variation in surface moisture, plus some surface temperature variation, gives a cloud base temperature between 2°C and -5°C. Surface observations from three airports near Edmonton indicate that a cloud base temperature of -5°C is most realistic. In that case the graupel must have grown at temperatures between -20 and -30°C. Also shown in the May 17 data are the T vs. δ_c values for the possibility of warmer cloud temperatures indicating that the graupel grew on an average at -18°C. This exercise clearly shows the need to know cloud base temperatures accurately if the model is to be used to estimate growth temperatures of graupel or hail.

MAY 23. This was a showery day in Banff National Park. A vapour sample was taken while ascending to Bow Pass (altitude about 2.1 km) where falling snow and snow pack was collected. A vapour sample was also taken while descending after the precipitation had ended. The vapour sample with the high δ_v (-22.3 °/oo) was taken in the evening during descent towards Calgary and remote from showers.

Snow from the top three millimeters of the snow pack at Bow Pass was collected for comparison to the falling snow since it seemed to have fallen recently. There is a discrepancy in these samples of 2 $^{\circ}/_{\circ\circ}$ which is difficult to explain. The cloud base was near to the altitude of Bow Pass where the temperature and dew point were 2.5°C. Using this information and equation (16) the growth temperatures of the snow were about -5°C for the falling snow and -15°C for the top 3 mm of the snow pack. However, there are two reasons why this model does not represent snowfall from what was probably primarily orographic snow. First, there is likely a significant precipitation efficiency in which case the δ value of the precipitation would be lower than that calculated at a given temperature level (see Figure 1). The second problem lies with the fact that the growth process of the snow in this case appeared to be primarily deposition (the opposite of sublimation) since the crystals were only lightly rimed. The reader is referred to Miyake et al. (1968) for calculations involving an open system in the non-equilibrium and the use of fractionation factors applicable to sublimation-deposition processes.

The snow pack compares well in delta value with the mountain creek water collected the previous day if some enrichment of creek water through evaporation before runoff is taken into account.

<u>JUNE 3</u>. δ_v is higher than on previous days, probably because the vapour sample was taken in the afternoon when thundershowers were widespread. δ for two rain samples which contained some small hail are similar, but considerable evaporation of the precipitation must have occurred, since their δ indicates a mean growth temperature of only -2°C. The vapour sample may indicate $H_2{}^{18}O$ enrichment of the vapour through evaporation of precipitation.

JUNE 5. The high delta values indicate that rather strong evaporation was probably occurring. The showers were light. The variation of delta in these rain samples also indicates considerable variation in the amount of evaporation below cloud. Strong evaporation is also indicated by the fact that, without taking into account evaporation, the model of equation (16) would indicate that the rain formed near or below the cloud base.

JULY 3. No showers occurred on July 3, but on the previous day, many hailstorms occurred between Calgary and Edmonton. A vapour sample taken at Red Deer showed high δ_v ($-22.5\ ^{o}/oo$) in the mid-morning.

JULY 4. A vapour sample was taken before 1800h when thundershowers began in the area. δ_v was considerably lower ($\delta_v = -27\ ^{o}/oo$) than the day before indicating regional advection of air with lower δ_v than the previous day. Violent thundershowers began north of Red Deer around 1800h and continued until after midnight as they moved eastward.

1900h. Three consecutive samples of mixed rain and hail were obtained in about five minutes as a shower approached the stationary sampling vehicle. During this time the δ value of the precipitation fell from -17.5 to $-19\ ^{o}/oo$, indicating decreasing enrichment due to below cloud evaporation as the below cloud relative humidity increased. This phenomenon has been studied by Hage et al. (1975), Miyake et al. (1968) and Craig et al. (1963).

2000h. A sample of hail was collected at the side of the road. It had fallen from a different thundershower than the 1900h samples, but it yielded a δ value much like the previous mixed rain and hail samples. The hail was about 5 mm in diameter. The growth temperature of the hail as indicated by the model is about -3°C which is unrealistic. Apparently the δ_v for the afternoon vapour sample was unrealistically low in the sense that it did not represent the vapour feeding the evening thundershowers.

2100h. Two samples of rain from another shower continue to yield similar delta values.

2400h. A very violent thundershower occurred during which four centimeters of rain fell in ten minutes. Small hail was separated from the rain and its δ value was determined. In such violent showers little below cloud evaporation could occur as is indicated by the very low δ value of the rain, the lowest of all our samples. In fact, the rain's δ value was lower than that of the hailstone cores which were separated from the rain. The outer part of the hailstone is assumed to have melted. The conclusion is that the center of the hailstones were formed at a warmer level of the cloud than the water which made up the rain. This is one further example of hail embryos coming from the lower levels of a cloud. Jouzel et al. (1975) found similar results in three Alberta hailstones. This was the experiment which led us to seek very heavy showers during the next two summers.

The first vapour sample was taken over a period of two hours followed by the second sample which was taken over a period of two hours during which showers were developing in the area. Studies in

1975 and 1976, to follow, indicate that δ_v varies considerably with time. All precipitation samples plotted in Figure 2 were from different showers, so they are difficult to compare. The higher δ_v value indicates that the samples were formed near the freezing level of the cloud. Clearly, the δ_v values from the early afternoon and late afternoon are not high enough to represent the vapour feeding the evening showers if below cloud evaporation is not taken into account.

JULY 9. Two vapour samples collected in the late morning and early afternoon of July 9 have very high values (-20 °/oo), apparently because the ground was wet. It had rained continuously the day before. It was a relatively hot day, surface temperature 24°C, and showers developed in the evening. δ values of hail samples are about 5 °/oo lower than the rain which contained some ice. The growth temperature of the hail as indicated by the model is about -20°C.

JULY 10. The delta value of the vapour sample (-24.9 °/oo) is a representative value for a sunny summer day in Alberta. The ground was dry in Edmonton and the dew point was a typical summer value of 9°C.

JULY 11. This was a day of continuous rain so that one expects the vapour to be in equilibrium with the rainwater. In this case the rain samples would have the same δ value as the cloud droplets at the LCL calculated from the model. Of course, the LCL does not exist since this is not a day of convective weather.

3.3 Discussion of 1975 Results

Figure 3 displays the results of the 1975 experiments. The same general trends as those found in 1974 observations are evident. Those dates when samples of vapour and precipitation are available are stressed in this discussion.

JUNE 16. Calculated temperatures of hail formation are high (0 to -5°C). It is evident that the vapour sample taken in the early afternoon does not have a high enough delta value to represent the evening showers.

JUNE 17. The vapour sample was taken during a rain shower so that the rain is nearly in equilibrium with the vapour.

JUNE 18. Four consecutive vapour samples were taken between morning and afternoon. Morning fog dissipated early. Nearly overcast stratocumulus developed by noon. In the afternoon the cloud dissipated as humidity fell. The first vapour sample has an average delta value because it is in equilibrium with the wet ground. The second sample has a high delta value, probably because this was taken just as the last surface water was evaporating. The last surface water would be very rich in $H_2{}^{18}O$. The third vapour sample indicates a normal delta value that has returned with continued development of stratocumulus cloud. The fourth sample was taken late in the afternoon as the dew point fell and the cloud dissipated. Its delta value is low because dry air of lower delta value is being advected into the area.

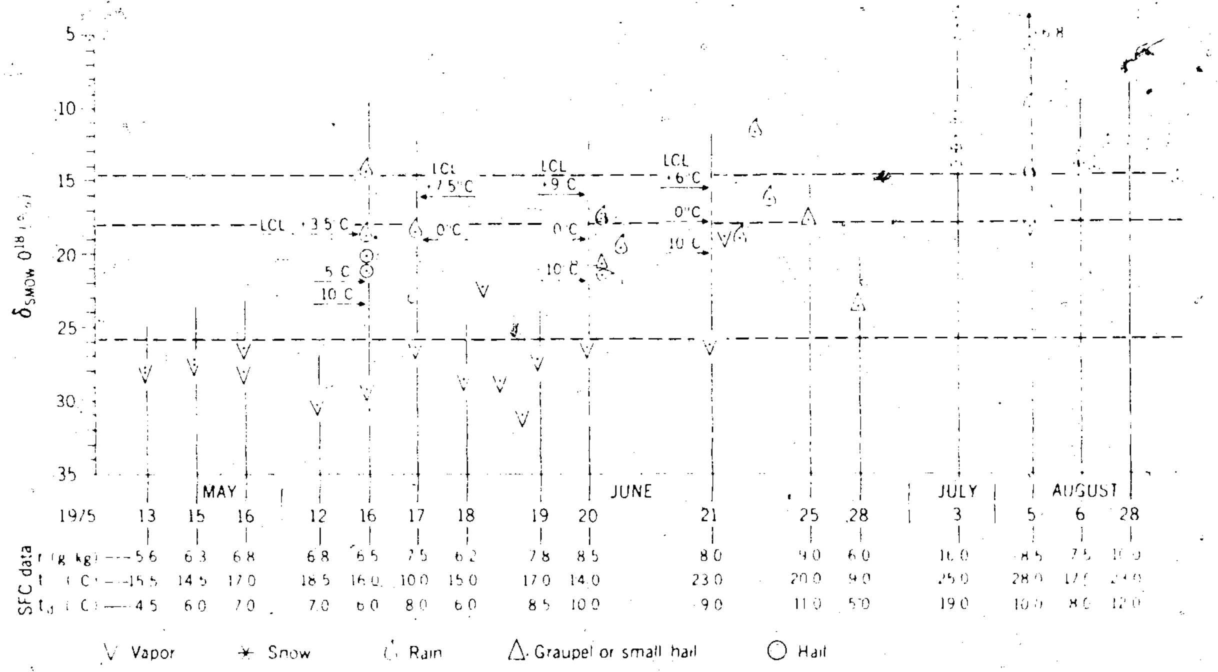

Figure 3. $H_2{}^{18}O$ in vapour and precipitation in 1975. The dashed lines represent average delta values of vapour, hail and rain for the 1974, 1975 and 1976 studies.

JUNE 20. A vapour sample was taken in the early afternoon when light showers were developing. The first precipitation sample consisted of mixed rain and hail from early in a shower. Its high delta value indicates that considerable enrichment of heavy isotope was occurring. Later during the shower, rain and hail were separated and they had similar delta values indicating a temperature of formation in the cloud of about -5°C. Their similar delta values also indicate little below cloud enrichment due to evaporation if one assumes that the liquid portion is melted hail. One final rain sample near the end of the shower had an intermediate delta value.

JUNE 21. The large difference between the delta values of the vapour is much like that which occurred on June 18. This also was a day which began with the ground wetted by the previous day's shower activities. Since each rain sample was from a different shower, the large variation in the delta values of the rain may be attributed to variations in the vapour's delta values as well as to differing degrees of below cloud evaporation.

JULY 3. Unfortunately, the vapour sample for this date was lost in the laboratory. This was a day of heavy thundershowers and some walnut-sized hail was reported but none was sampled. In the early evening three samples of pea to grape-size hail were obtained from two different storms. Their relatively high delta values (-10.8, -12.5, and -13.3 °/oo) indicate that the vapour feeding the cloud must have been rich in ^{18}O by about 5 °/oo. This condition appears to have occurred again on August 6 and August 28, two more hail days when no vapour samples were collected.

AUGUST 5. The delta value of the vapour (-18 $^o/oo$) and of one sample of hail (+6.8 $^o/oo$) are probably unrealistically high. A second sample of small hail had a near normal delta value (-17.6 $^o/oo$). There were problems with the mass spectrometer during the analysis of this date's samples.

3.4 Discussion of 1976 Results

Observations for 1976 are given in Tables A-III and B-III (Appendix). Final results are shown in Figure 4. In general, trends similar to those of 1974 and 1975 are observed in the 1976 measurements. Some of the interesting situations are discussed below.

JUNE 19. No vapour sample was collected on this day prior to the showers. However, the δ values of the precipitation samples were measured and are shown in Figure 4. This figure indicates that the δ value for vapour collected on June 18 and 21 is around -28 $^o/oo$. This δ value is used to calculate the cloud temperatures. Arrows shown in Figure 4 indicate that the rain and graupel were formed between the -8 and 0°C levels.

JUNE 30. Four bagged vapour samples were collected, the last three on the top of a 15-storey building. The day had extensive instability but very little precipitation was reaching the ground. The very high delta value (-9.5 $^o/oo$) was recorded at a time when virga (evaporating precipitation) was very close to the collection point. Completely evaporated rain could give such a high value.

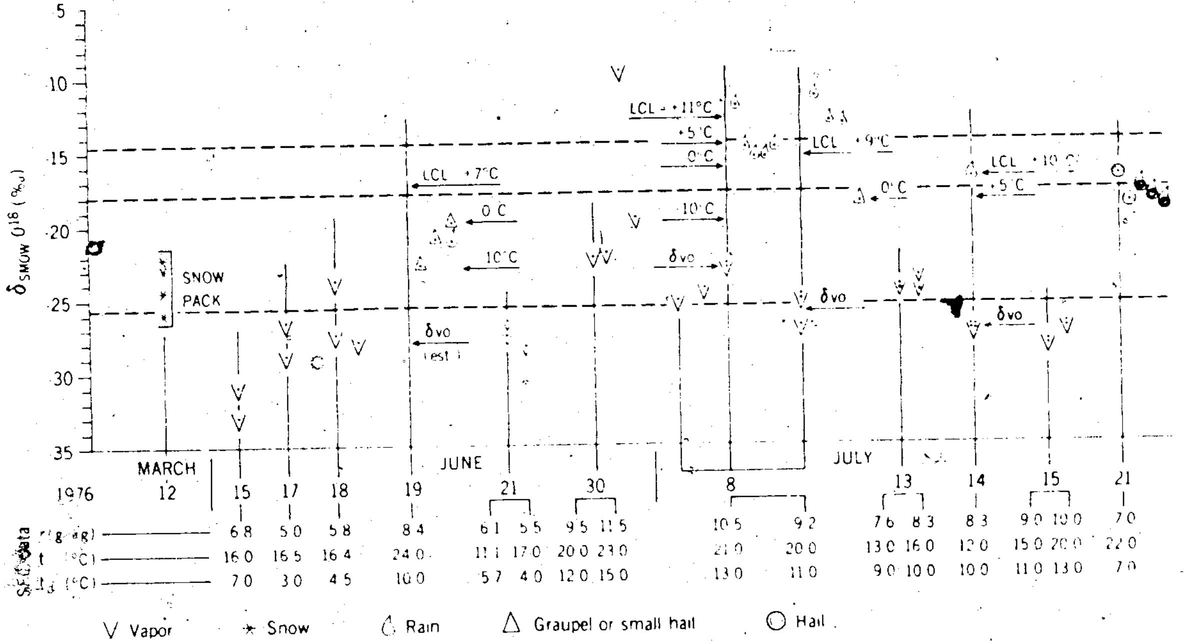

Figure 4. $H_2{}^{18}O$ in vapour and precipitation in 1976. The dashed lines represent average delta values of vapour, hail and rain for the 1974, 1975 and 1976 studies.

JULY 8. Seven vapour samples were collected. Measured δ values are typical of the vapour from central Alberta. δ_v varies by about 4 $^o/oo$. The causes of this variation are not yet clear. Calculations, using equation (16) and two sets of values for surface temperatures and δ_{vo}, were performed. These calculations suggest that the small hail formed at the 0^{o}C or the -5^{o}C level. If the suggested model is correct, there is clearly a need for the vapour feeding the cloud to be higher in delta value than that measured at the ground.

JULY 14. Four samples of vapour taken in the laboratory over a period of three hours showed little variation in their delta values. This shows that the vapour sampling technique can give consistent results.

3.5 General Discussion

Calculated mean δ values from the data given in Appendix B are -26.0, -23.8, -17.9 and -14.6 for vapour, snow, hail, and rain, respectively. The mean value of δ_v is lower by about 11 $^o/oo$ than the mean δ value for rain. O'Neill and Epstein (1966) found that δ_v fell to values of between -20 and -24 $^o/oo$ during a California stormy period while calm weather conditions gave $\delta_v \simeq -14$ $^o/oo$. Other studies of the isotopic content of water vapour include those by Ehhalt (1974) who reported the vertical profiles of HTO, HDO and H_2O in the troposphere for some places in the United States. In most cases the heavy isotope content of the water vapour decreases as a function of the altitude. These observations imply that δ_v measured at the surface would be lower on days of deep convection. The large variations and mean values of δ_v found in this study are consistent with those found by Facy et al. (1963) at a continental location. In Alberta, summer convective precipitation comes mainly from locally evaporated water. Mean δ_v values and variations of δ_v for maritime locations are considerably lower as reported in the studies discussed above and in Craig and Gordon (1965).

In general, the rain samples show higher δ values than graupel or hail. This does not necessarily indicate that rain was formed at a lower level in the cloud since evaporation below cloud base would enrich the heavy isotope in precipitation. Studies of this phenomenon, which do not necessarily occur in isotopic equilibrium or by Rayleigh distillation, have been published by Hage et al. (1975), Miyake et al. (1968), Dansgaard (1964), Craig et al. (1963), Friedman et al. (1962) and Stewart (1975).

Four samples of precipitation (Table B-1) were analyzed for D content in order to check the established relationship between δD and $\delta^{18}O$. Craig (1961) observed the following linear relationship between $\delta^{18}O$ and δD using four hundred samples of naturally occurring water.

$$\delta D = 8\,\delta^{18}O + 10 \quad (^{o}/oo) \qquad (4)$$

Dansgaard (1964) using least square analysis on monthly values from individual stations found slopes and intercepts that varied from 3.5 to 8.0 and -30 to +30, respectively. Recently, for Edmonton precipitation, Hage, Gray and Linton (1975) have calculated the slope and intercept of equation (4) to be 7.8 and +0.4, respectively. Using mean values of $\delta^{18}O = -19.2\ ^{o}/oo$ from four 1974 samples, slope = 7.8 and intercept = +0.4, the computed value of δD is found to be -149 $^{o}/oo$. This value is in excellent agreement with the mean value of -150 $^{o}/oo$ found in this work.

Using linear regression on the mean monthly delta values and mean monthly temperatures (T, ^{o}C) for only the summer months at Edmonton, Linton (1972) obtained the following equation:

$$\delta^{18}O = 0.37\ T - 20.0\ (^{o}/oo). \qquad (17)$$

The slope and intercept of equation (17) has been discussed in detail by Hage, Gray and Linton (1975). There is no intention to discuss the climatology of isotopes in precipitation and repeat previous discussions here. It is sufficient to mention that the isotopic data obtained in the present study are consistent with equation (17) and support Hage et al.'s (1975) argument that almost all warm season precipitation in central Alberta, shielded by high mountain ranges to the west, originates from water vapour produced by re-evaporation of precipitation over land (including transpiration).

Recently Jouzel et al. (1975) have presented a detailed interpretation and discussion of the isotopic measurements made on three hailstones produced by a storm which occurred on August 7, 1971, in Alberta. The maximum and minimum δD values as a function of the radius within the hailstones, taken from their Figures 5 and 6, are between -125 and -150 $^{o}/oo$. Using these values and Hage et al.'s slope and intercept in equation (3), $\delta^{18}O$ has been calculated, and it is found to vary between -15.4 and -19.2 $^{o}/oo$. This is in good agreement with the majority of the δ values observed for the hail and graupel in the present study.

CHAPTER 4

CONCLUSIONS

4.1 Summary of the Data and the Model

This study was designed to sample vapour, hail and graupel on showery days. The samples were to be analyzed for $H_2{}^{18}O$, and the resulting data were to be used to understand and learn about precipitation formation processes. Some difficulties in controlling field, laboratory, and theoretical studies arose, but they did not obscure some very interesting observations. During the three years of these studies, individual field experiments became more directed and controllable. For instance, studies of the variation of the vapour delta values on an hourly or even on shorter time scale became a necessary objective. Also, the study of rain during very heavy showers to eliminate the below cloud evaporation problem became an objective. As the time progressed it became apparent that graupel, i.e., snow pellets, constitute the only precipitation mechanism that comes very near to really "locking in" the isotopic content of the cloud droplets.

The majority of the results suggest that small hail and graupel appear to grow in the warm regions of the cloud ($T \approx 0$ to $-15^{\circ}C$). This temperature range, calculated using the simple model, is warmer than what one would expect. Use of a more detailed isotopic cloud model which includes a finite precipitation rate (open models) would make this temperature range even warmer. The experiments showed that the delta value of water vapour is quite variable on an hour-to-hour basis during showery weather in Alberta. Therefore, delta values of vapour measured at the ground must be applied with caution to isotopic models of convective precipitation formation. Simultaneous measurements of deuterium and oxygen-18 would give better insight as well as a "double check" into the reliability of the numerical models used.

During 1974, the observed delta values of vapour were in the range of -31.3 to -18.5 °/oo. The majority of these values are close to -25 °/oo. Reasonable explanations of these variations have been given in terms of the hourly and daily hydrological cycle. Mean delta value for the rain (-15.7 °/oo) obtained in the present study was about 4 °/oo higher than the previous studies. Only 23 samples of rain were collected and analyzed in 1974. Such a small sample does not represent the average seasonal delta value of rain for Alberta because many samples were from light showers. Under such conditions, evaporation during rain falling would cause the delta values to rise. The 1975 and 1976 data lead to similar observations.

The present results support previous studies which suggest that almost all warm season precipitation in central Alberta originates from water vapour produced by re-evaporation of local water.

4.2 Suggestions for Further Work

The observed isotopic variations have been interpreted using a simple cloud model and surface meteorological data only. It would be worthwhile to investigate and interpret the present data further using all available upper air observations and more detailed models.

The present and previous investigations on isotopes in precipitation suggest that a more practical use of models would involve some simple and continuous method of sampling the water vapour in the air. It is suggested that new methods and procedures of sampling water vapour at the surface and aloft should be developed.

It is easy to suggest that someone sample cloud droplets under a variety of weather conditions. Isotopic information on cloud droplets would be crucial in the selection of a model for practical applications. However, such observations have been suggested for years but no one has come up with a method to sample cloud droplets without having them partially evaporate.

It is suggested that future studies should include simultaneous measurement of deuterium and oxygen-18.

Experiments on cloud seeding to suppress hail have been underway in Canada and the United States for more than two decases. All the scientific evidence obtained so far is inconclusive in that it does not answer the question: "Does cloud seeding work?" The variations of $H_2{}^{18}O$ and HDO in precipitation from seeded and nonseeded clouds has not been studied previously. It is felt that the study of seeding material (AgI) in conjunction with the isotopes in total precipitation, both rain and hail, from seeded and nonseeded clouds might yield clues ~~to~~ assess the effectiveness of hail suppression experiments.

REFERENCES

Baily, I.H., J.R. Hulston, W.C. Macklin and J.R. Stewart, 1969: On the Isotopic Composition of Hailstones. Journal of the Atmospheric Sciences, 26, 689-694.

Byers, H.R., 1965: Elements of Cloud Physics. The University of Chicago Press.

Charlton, R.B., J. Gray, and H.S. Sandhu, 1975: Modelling Precipitation Processes with Stable Isotopes. Abstracts of Papers Presented at the 9th Annual Congress of Canadian Meteorological Society, Vancouver, Canada.

Chisholm, A.J., 1970: Alberta Hailstorms: A Radar Study and Model. Ph.D. Thesis, McGill University, Montreal, Quebec, 237 pp.

Coleman, M.L., and J. Gray, 1972: An adjustable Gas Inlet System for an Isotope Mass Spectrometer. Reviews of Scientific Instruments, 43, 1501-1503.

Craig, H., 1961: Isotopic Variations in Meteorite Waters, Science, 133, 1702, 1703.

Craig, H., 1961: Standard for Reporting Concentrations of Deuterium and Oxygen 18 in Natural Waters. Science, 133, 1833-1834.

Craig, H., L.I. Gordon, and Y. Horibe, 1963: Isotopic Exchange Effects in Evaporation of Water: I. Low-Temperature Experimental Results. Journal of Geophysical Research, 68, (17), 5079-5087.

Craig, H., and L.I. Gordon, 1965: Isotopic Oceanography: Deuterium and Oxygen 18 Variation in the Oceans and the Marine Atmosphere. Proceedings of Symposium at the University of Rhode Island, 1964, 277-374.

Dansgaard, W., 1961: The Isotopic Composition of Natural Waters. Meddelser Im Bromland, 165, (2), 1-120.

Dansgaard, W., 1964: Stable Isotopes in Precipitation. Tellus, 16, 436-468.

Dincer, T., 1968: The Use of Oxygen 18 and Deuterium Concentrations in the Water Balance of Lakes. Water Resources Research, 4, 1289-1306.

Ehhalt, D.H., 1974: Vertical Profiles of HTO, HDO, and H_2O in the Troposphere. NCAR Technical Note, Number 101.

Epstein, S., and T. Mayeda, 1953: Variations of ^{18}O content of waters from natural sources. Geochim Cosmochim. Acta, 4, 213-224.

Facy, L., L. Merlivat, G. Nief, and E. Roth, 1963: The Study of the Formation of a Hailstone by Means of Isotopic Analysis. Journal of Geophysical Research, 58, 3841-3848.

Fletcher, N.H., 1969: The Physics of Rain Clouds. Cambridge University Press.

Friedman, I., L. Machta, and R. Soller, 1962: Water-Vapour Exchange Between a Water Droplet and Its Environment. Journal of Geophysical Research, 67, 2761-2766.

Hage, K.D., J. Gray, and J.C. Linton, 1975: Isotopes in Precipitation in Northwestern North America. Monthly Weather Review, 103, No. 11, 958-966.

Horibe, Y., K. Shegehore, and Y. Takakakuwa, 1973: Isotopic Separation Factor of Carbon Dioxide-Water System and Isotopic Composition of Atmospheric Oxygen. Journal of Geophysical Research, Washington, D.C., 78, (15), 2625-2629, and other references therein.

International Atomic Energy Agency, 1969: Environmental Isotope Data No. 1. Tech. Rep. Ser. 96, International Atomic Energy Agency, Vienna.

International Atomic Energy Agency, 1970: Environmental Isotope Data No. 2. Tech. Rep. Ser. 117, International Atomic Energy Agency, Vienna.

International Atomic Energy Agency, 1971: Environmental Isotope Data No. 3. Tech. Rep. Ser. 129, International Atomic Energy Agency, Vienna.

Jouzel, J., L. Merlivat, and E. Roth, 1975: Isotopic Study of Hail. Journal of Geophysical Research, 80, 5015-5030.

Knight, C.A., D.H. Ehhalt, N. Roper, and N.C. Knight, 1975: Radial and Tangential Variation of Deuterium in Hailstones. Journal of the Atmospheric Science, 32, 1990-2000.

Linton, J.C., 1972: A Study of the Oxygen 18 Content in Precipitation at Edmonton, Alberta. M.Sc. Thesis, University of Alberta, Edmonton, Canada, 81 pp.

Macklin, W.C., L. Merlivat, and C.M. Stevenson, 1970: The Analysis of a Hailstone. Quarterly Journal of the Royal Meteorological Society, 96, 472-486.

Macklin, W.C., C.A. Knight, H.E. Moore, N.C. Knight, W.H. Pollock, J.N. Carras, and S. Thwaites, 1977: Isotopic, Crystal and Air Bubble Structures of Hailstones. Journal of the Atmospheric Sciences, 34, (6), 961-967.

Majzoube, M., G. Nief, and E. Roth, 1968: Variations and Comparisons of Deuterium and Oxygen 18 Concentrations in Hailstones. Proceedings of the International Conference on Cloud Physics, August 26-30, Toronto, Canada.

Mason, B.J., 1971: The Physics of Clouds. Second Edition, Oxford Clarendon Press.

Mason, B.J., 1975: Clouds, Rain and Rainmaking. Second Edition, Cambridge, Cambridge University Press.

Merlivat, L., G. Nief, and E. Roth, 1965: Formation de la Grele et Fractionnement Isotopique du Deuterium, Abhandlunger der Deutschen Akademic der Wissenschafter zu Berlin, 7, 839-853.

Miyake, Y., O. Matsubaya, and C. Nishihara, 1968: An Isotopic Study on Meteoric Precipitation. Papers in Meteorology and Geophysics, 19, 243-266.

O'Neil, J.M. and S. Epstein, 1966: A Method for Oxygen Isotope Analysis of Milligram Quantities of Water and Some of its Applications. Journal of Geophysical Research, 71, 4955-4961.

Rogers, R.R., 1976: A Short [illegible] in Cloud Physics. Pergamon Press.

Roos, D.v.d. S., H. Schooling, and J.C. Vogel, 1977: Deuterium in Hailstones Collected on 29 November 1972. Quarterly Journal of the Royal Meteorological Society, 103, 751-767.

Rychkov, A.M., and V. Ye. Vetshteyn, 1976: Variations of D/H and $^{18}O/^{16}O$ in Atmospheric Precipitation in Certain Climatic Zones of the Asiatic Soviet Union. English Translation of Russian Journal; Atmospheric and Oceanic Physics, 12, 451-454.

Stewart, M.K., 1975: Stable Isotope Fractionation due to Evaporation and Isotopic exchange of Falling Waterdrops: Applications to Atmospheric Process and Evaporation of Lakes. Journal of Geophysical Research, 80, 1133-1146.

West, K.E., 1972: H_2O^{18}/H_2O^{16} Variations in Ice and Snow of Mountainous Regions of Canada. Ph.D. Thesis, University of Alberta, Edmonton, Canada.

APPENDIX A

Meteorological Data for the Sampling Period

Explanation of Sample Code

YR - Year during which sample was collected

MO - Month of the year

DA - Day of the month

LDT - Local daylight time

TYPE - Type of sample

V - Vapour

R - Rain

H - Hail

G - Graupel

RH - Rain and hail mixed

Table A-1

Meteorological Data for the Sampling Period During 1974

Sample YR,	MO,	DA,	LDT,	TYPE	Temp °C	Dewpoint °C	Mixing Ratio g/kg	LCL Temp °C	Altitude Sample m	Sampling Location and Weather Remarks
74	05	15	1310-1530	V1	11.5	2	4.8	0	670	U of A
74	05	15	1600	G1	↓	↓	↓	↓	↓	Game Farm 1500 EG 30 SCT 45 BKN RW-- /9/4/ VIRGA 1500 XD 40 SCT 55 SCT/9/1/ All four showers cont. ice pellets
74	05	15	1600	G1						
74	05	15	1600	G1						
74	05	15	1600	R1						
74	05	15	1600	R2						
74	05	15	1600	R2						
74	05	16	1000	V1	12.5	3	5.2	0	670	U of A, RW- Frequent
74	05	17	1230	G1	7 (7)	1.5(-2.5)	4.5(3.3)	0 (-5)	670	S EG, Graup. dry, RW- VCTY
74	05	17	1330	V1	7 (7)	1.5(-2.5)	4.5(3.3)	0 (-5)	670	Slow pumping
74	05	21	2200	V1	10	1	4.5	NA	1400	Banff, Sunny
74	05	22	1500	V1	13	2	5	NA	1690-1100	Sunshine Mtn., Sunny
74	05	23	1600-1800	V1	7 (2)	6 (2)	7 (5)	(2-3)	1400-2100	Banff to Bow Pass, RW-
74	05	23	1800-2000	V2	9	1	5	NA	1800-1100	Bow Pass to YC, RW- ended
74	05	23	1700	R1	7	6	7	(2-3)	1500	Lake Louise turn, MOD RW
74	05	23	1800	S1	2	2	5	2,3	2100	Falling Snow, Bow Pass, SW-
74	05	23	1800	S2	2	2	5	2,3	2100	0.5 cm-deep snow

continued...

Table A-1, continued:

Sample YR,	MO,	DA,	LDT,	TYPE	Temp °C	Dewpoint °C	Mixing Ratio g/kg	LCL Temp °C	Altitude Sample m	Sampling Location and Weather Remarks
74	05	23	1800	S3	NA	NA	NA	NA	2100	30 cm-deep snow
74	05	23	1800	S4	NA	NA	NA	NA	2100	25 cm-deep snow
74	05	24	1130	V1	14	0	4	-3	1100-900	Calgary to ALHAP, Sunny
74	06	03	1600- 2030	V1	18	4.5	5.7	1.5	670-1000	U of A to RM,
74	06	03	1400	R1	10	6	6	NA	↓	Showers with ice
74	06	03	1400	R2	10	6	6	NA	↓	
74	06	05	1500	V1	18	4.5	5.7	1.5	670	N of Edmonton, 3 separate RW-
74	06	05	to	R1	↓	↓	↓	↓	↓	
74	06	05		R2	↓	↓	↓	↓	↓	
74	06	05	1900	R3	↓	↓	↓	↓	↓	
74	06	06	pm	R1	17	5	6	2	670	St. Albert, RW-
74	06	08	1515	R1	17.5 EG	4.5 EG	5.5	1	670	Edmonton, R1 is 1st precip.
74	07	03	1800	V1	19	9.5	8.5		900	ALHAP, Sunny

continued...

Table A-1, continued:

Sample YR,	MO,	DA,	LDT,	TYPE	Temp °C	Dewpoint °C	Mixing Ratio g/kg	LCL Temp °C	Altitude Sample m	Sampling Location and Weather Remarks
74	07	04	1730	V1	17.5	5.5	6.7	4	900	ALHAP VCTY Evening typical values: T=21, T_d=7 r=7 g/kg
74	07	04	1900	R1	↓	↓	↓	↓	↓	NW of ALHAP 3 successive samples of rain with ice
74	07	04	1900	R2	↓	↓	↓	↓	↓	
74	07	04	1900	R3	↓	↓	↓	↓	↓	
74	07	04	2000	H1	↓	↓	↓	↓	↓	Rimbey
74	07	04	2100	R4	↓	↓	↓	↓	↓	Near Rimbey
74	07	04	2400	H2	~8	~8	~7.5	NA	850	50 km E of ALHAP
74	07	04	2400	R5	~8	~8	~7.5	NA	850	Severe RW++ Ice separated
74	07	05	1300-1500	V1	20	6	6.5	2	900	ALHAP, slow pumping
74	07	05	1600-2000	V2	16	6	6.5	4	900-1000	ALHAP to RM, fast pumping, Pumping off during rain
74	07	05	1730	R1	↓	↓	↓	↓	↓	25 km W of QF, early in RW-
74	07	05	2027	R2	↓	↓	↓	↓	↓	37 km WNW of QF, after 20 min.
74	07	05	2047	R3	↓	↓	↓	↓	↓	37 km WNW of QF, contained ice
74	07	05	2131	H1	↓	↓	↓	↓	↓	37 km WNW of QF, shot, soft
74	07	05	2155	H2	↓	↓	↓	↓	↓	32 km NNE of QF, 5 cm deep in ditch. Large pea - max size
74	07	05	2342	H3	↓	↓	↓	↓	↓	60 km NE of QF, hail on road
74	07	05	2348	R4	↓	↓	↓	↓	↓	60 km NE of QF, RW-
74	07	06	1745	R1	19	9	8	7	900	ALHAP very early in RW-
74	07	07	1700	R1	16	4	5.5	1	1000	RM, RW- with ice

continued...

Table A-1, continued:

Sample YR, MO, DA, LDT,				TYPE	Temp °C	Dewpoint °C	Mixing Ratio g/kg	LCL Temp °C	Altitude Sample m	Sampling Location and Weather Remarks
74	07	09	0926-1247	V1	18	14	11	NA	900	ALHAP, Ground wet, fast flow
74	07	09	1323-1500	V2	24	13	11	11	900	ALHAP, slow flow
74	07	09	2043	H1	↓	↓	↓	↓	900	104 km NW QF, Hail in ditch
74	07	09	2205	R1					700	112 km N QF, Some ice
74	07	09	2225	H2					700	120 km N QF, Hail in ditch
74	07	10	1530-1730	V1	22	9	8		670	U of A, Tandem run, sunny
74	07	11	1512-1650	V1	16	11	9	9	670	U of A, Fast pumping, rainy
74	07	11	1630	R1	↓	↓	↓	↓	↓	U of A, Rain
74	07	11	1630	R2						U of A, Puddle water

Table A-11

Meteorological Data for the Sampling Period During 1975

Sample YR,	MO,	DA,	LDT,	TYPE	Temp °C	Dewpoint °C	Mixing Ratio g/kg	LCL Temp °C	Altitude Sample m	Sampling Location and Weather Remarks
75	05	13	1450 to	V1	15.5	4.5	5.6	2	670	U of A Partly cloudy No rain for 3 days
75	05	13	1730	V2	↓	↓	↓	↓	↓	U of A
75	05	15	1015 to	V1	14.5	6	6.3	4	670	U of A, Slow flow
75	05	15	1300	V2	↓	↓	↓	↓	↓	U of A, Fast flow
75	05	16	1045 to	V1	17	7	6.8	4	670	U of A - 50°C cirrus cloud
75	05	16	1330	V2	↓	↓	↓	↓	↓	U of A - 70°C
75	06	12	1400	V1	18.5	7	6.8	4	900	ALHAP, mid cloud
75	06	16	1200- 1545	V1	15	8.5	7.5	7	900	ALHAP, Light shower
75	06	16	1910	R1	16	6	6.5	3.5	↓	ALHAP, RW- 24 km NW of ALHAP Hail is from 2nd burst of RW
75	06	16	1838	R2	↓	↓	↓	↓	↓	
75	06	16	1838	H1	↓	↓	↓	↓	↓	
75	06	16	1850	H2	↓	↓	↓	↓	↓	
75	06	17	1430	V1	10	9	8	NA	900	ALHAP - OVCST WITH RW- VAPOR DURING RW-
75	06	17	1450	R1	10	8	7.5	NA	900	10 SCT 25 OVC

continued...

Table A-II, continued:

Sample YR, MO, DA, LDT,				TYPE	Temp °C	Dewpoint °C	Mixing Ratio g/kg	LCL Temp °C	Altitude Sample m	Sampling Location and Weather Remarks
75	06	18	1030	V1	11	7.5	7.5	NA	900	ALHAP - Fog till 0800 20 CU 2 Max Dew Point
75	06	18	1245	V2	14	6	5.5	4	↓	40 CU 9
75	06	18	1500	V3	16	6	6.5	3.5	↓	40 CU 8
75	06	18	1730	V4	17	3	5.2	0	↓	50 CU 3 Dry air
75	06	19	1645	V1	17	8.5	7.8	9	900	ALHAP, 55 ⦶ CU at 1800 Evening RW-
75	06	20	1220- 1320	V1	14	10	8.5	9	900	ALHAP, 2 RW- during V sample OVCST AS with CU
75	06	20	1442 -	RG1	↓	↓	↓	↓	↓	ALHAP, Rain & hail mixed, RW mod.
75	06	20	1442	G1	↓	↓	↓	↓	↓	ALHAP, Shot is from rain
75	06	20	1442	R2	↓	↓	↓	↓	↓	ALHAP, Rain, hail removed
75	06	20	1450	R3	↓	↓	↓	↓	↓	ALHAP, Rain, hail ended
75	06	21	1148 to	V1	20.5	11.5	10	10.5	900	ALHAP, clear morning
75	06	21	1432	V2	23	9	8	6	900	ALHAP to Sylvan Lake
75	06	21	1530	R1	↓	↓	↓	↓	↓	16 km NW QF, ice in rain
75	06	21	1610	R2	↓	↓	↓	↓	↓	19 km WNW QF, rain only
75	06	21	2100	R3	↓	↓	↓	↓	↓	32 km W QF, all storms moved slowly to SE

continued...

Table A-11, continued:

YR,	MO,	DA,	Sample LDT,	TYPE	Temp °C	Dewpoint °C	Mixing Ratio g/kg	LCL Temp °C	Altitude Sample m	Sampling Location and Weather Remarks
75	06	25	1940	G1	20 QF	11 QF	9	9	900	Red Deer
75	06	28	1140	G1	9 QF	5 QF	6	NA	900	ALHAP, morning showers
75	07	03	1202-1342	V1	26.5	19	15	17	900	ALHAP, Golf ball FCST
75	07	03	1702	R1	24	20	NA	NA	1000	67 km WNW QF, 10 min into rain
75	07	03	1800	R2	↓	↓	↓	↓	↓	51 km WNW QF, Walnut 60 km W of QF
75	07	03	2005	R3	↓	↓	↓	↓	↓	56 km WNW QF, RW+
75	07	03	2005	G1	24	16	↓	↓	↓	56 km WNW QF
75	07	03	2020	G2	24	16	↓	↓	↓	56 km WNW QF, Hail only precip, (grape)
75	07	03	2145	G3	22	16	↓	↓	900	80 km NW QF, Pea after RW-
75	07	03	P.M.		25 RM	19 RM	16	17.5	NA	p.m.temps from RM
75	08	05	1154-1500	V1	22	13.5	10.5	11.5	900	ALHAP
75	08	05	1637	R1	28 QF	10 QF	8.5	6	900	96 km NW QF
75	08	05	1747	G1	↓	↓	↓	↓	800	88 km NNE QF
75	08	05	1748	RG2	↓	↓	↓	↓	↓	" "
75	08	05	1753	G3	↓	↓	↓	↓	↓	" "
75	08	06	1338	R1	17 QF	8 QF	7.5	6	1000	85 km W QF
75	08	06	1338	G1	↓	↓	↓	↓	↓	↓
75	08	06	1345	G2	↓	↓	↓	↓	↓	
75	08	06	1353	G3	↓	↓	↓	↓	↓	W of QF?

continued...

Table A-II, continued:

Sample YR, MO, DA, LDT,				TYPE	Temp °C	Dewpoint °C	Mixing Ratio g/kg	LCL Temp °C	Altitude Sample m	Sampling Location and Weather Remarks
75	08	28	1502	R1	23 QF	12 QF	10	10	850	48 km NW of QF
75	08	28	1528	R2	↓	↓	↓	↓	850	61 km NW of QF
75	08	28	1648	R3	↓	↓	↓	↓	900	19 km NW of QF, 15 sec of pea
75	08	28	1744	R4	↓	↓	↓	↓	850	56 km NE of QF, R+
75	08	28	1750	R5	↓	↓	↓	↓	↓	56 km NE of QF, R+
75	08	28	1915	G1	↓	↓	↓	↓	↓	29 km N QF, pea from drift in ditch

Table A-III

Meteorological Data for the Sampling Period During 1976

Sample YR,	MO,	DA,	LDT,	TYPE	Temp °C	Dewpoint °C	Mixing Ratio g/kg	LCL Temp °C	Altitude Sample m	Sampling Location and Weather Remarks
76	03	12		S2	NA	NA	NA	NA	300	Ft. McMurray, Snow pack beside tailings pond. S1 was lost.
76	03	12		S3	↓	↓	↓	↓	↓	
76	03	12		S4	↓	↓	↓	↓	↓	
76	03	12		S5	↓	↓	↓	↓	↓	
76	06	15	1439 to	V1	16	7	6.8	5	670	U of A TESTS Normal pumping Brief R--, few CU
76	06	15	1613	V2	16	7	6.8	5	670	Slow pumping rate
76	06	17	1015	V1	16.5	3	5	0	670	U of A TESTS Bagged and condensed at same time
76	06	17	1015	V2	16.5	3	5	0	670	
76	06	18	0912	V1	16.4	4.5	5.8	2	670	U of A TESTS Bagged and condensed at same time
76	06	18	0912	V2	↓	↓	↓	↓	↓	Tandem test run
76	06	18	a.m.	V2		↓	↓	↓	↓	Vapor from outdoors
76	06	19	1700	G1	24 EG	10 EG	8.4	7	670	1.5 km SE of U of A, 1.5 cm max
76	06	19	1730	G2	↓	↓	↓	↓	↓	" , 1 cm from gnd
76	06	19	1750	R1	↓	↓	↓	↓	↓	" , water puddle
76	06	19	p.m.	G3	↓	↓	↓	↓	↓	16 km W of U of A
76	06	19	p.m.	G4	↓	↓	↓	↓	↓	"

continued...

Table A-III, continued:

Sample YR,	MO,	DA,	LDT,	TYPE	Temp °C	Dewpoint °C	Mixing Ratio g/kg	LCL Temp °C	Altitude Sample m	Sampling Location and Weather Remarks
76	07	08	1800	V5	20.5	13	10.5	11	900	Winfield, 100 km NNW QF
76	07	08	1801	V6	↓	↓	↓	↓	↓	2 minutes before
76	07	08	1802	V7						RW- during gusts
76	07	08	1606	R1	21	13	10.5	11	1000	Alder Flats R- rain begins
76	07	08	|	R2	|	|	|	|	|	110 km NW QF R moderate
76	07	08	to	R3	to	to	to	to	|	R moderate
76	07	08	↓	R4	↓	↓	↓	↓	|	R-
76	07	08	1700	R5	15.5	12	10	NA	↓	R- rain end
76	07	08	1804	R6	20.5	13	10.5	11	900	Winfield, R--
76	07	08	1810	R7	to	to	to	to	↓	100 km R-
76	07	08	1820	R8	19.5	9	8	NA		NNW QF R-
76	07	08	1850	G1	23 RM	9 RM	8 RM	6 RM	1000	Winfield, 100 km NW QF Shot size Typical P.M. RM Temps
76	07	13	0827 to	V1	13	9	7.6	NA	670	U of A, TESTS Normal pumping
76	07	13	0947	V2	"	"	"	|	|	Slow pumping
76	07	13	0955 to	V3	15	10	8.3	|	|	U of A, TESTS Normal pumping
76	07	13	1145	V4	"	"	"	↓	↓	Slow pumping
76	07	14	1130 to	V1	12	10.5	8.6	10	670	U of A, TESTS -54°C RW- ended 1145
76	07	14	1300	V2	"	"	"	"	"	-74°C

continued...

Table A-III, continued:

YR,	MO,	DA,	LDT,	TYPE	Temp °C	Dewpoint °C	Mixing Ratio g/kg	LCL Temp °C	Altitude Sample m	Sampling Location and Weather Remarks
76	07	14	1303	V3	11	10	8.3	10	670	U of A, TESTS -55°C RW- began 1300
			to		to					
76	07	14	1421	V4	14	10	8.3	9	↓	--70°C
76	07	14	1400	R1	NA	NA	NA	NA	↓	U of A, I.D. of sample poor
76	07	15	0900	V1	15	11	9	NA	670	U of A, TESTS Normal pumping High Cloud
			to							
76	07	15	1055	V2	"	"	"	"	↓	Fast pumping
76	07	15	1114-	V3	20	13	10	NA	↓	-54°C
76	07	15	1239	V4	"	"	"	"	↓	-40°C
76	07	21	p.m.	H1	22 RM	7 RM	7	4	1100	Hespero, 40 km WNW QF Rain and hail mixed
76	07	21	p.m.	H2	↓	↓	↓	↓	↓	
76	07	21	p.m.	RH4	↓	↓	↓	↓	↓	
76	07	21	p.m.	RH5	↓	↓	↓	↓	↓	
76	07	21	p.m.	RH6	↓	↓	↓	↓	↓	

APPENDIX B

Isotopic Analysis of Collected Samples

Explanation of Sample Code

YR - Year during which sample was collected

MO - Month of the year

DA - Day of the month

LDT - Local daylight time

TYPE - Type of sample

V - Vapour

R - Rain

H - Hail

G - Graupel

RH - Rain and hail mixed

Table B-1

Isotopic Analyses of Vapour and Precipitation Samples Collected During 1974..

Sample YR,	MO,	DA,	LDT,	TYPE	Volume Used mls	Pressure CO_2 mm Hg	(kPa)		$\delta^{18}O^{\#}$ $^{o}/_{oo}$	$\delta^{18}O_{SMOW}$ $^{o}/_{oo}$	Sample water comments
74	05	15	1310- 1530	V1	3	43	(5.7)		12.7*	-27.7	clear
74	05	15	1600	G1	3	43	(5.7)		19.9*	-20.8	residue
74	05	15	1600	G1	3	43	(5.7)	(6.8)	19.8*	-20.9(-152)	residue
74	05	15	1600	G1	2.2	40	(5.3)		19.5*	-21.2	residue
74	05	15	1600	R1	3	46	(6.1)	(15.2)	21.6*	-19.1(-145)	turbid
74	05	15	1600	R2	3	46	(6.1)	(19.2)	21.9*	-18.9(-142)	residue
74	05	15	1600	R2	3	43	(5.7)		22.2*	-18.6	residue
74	05	16	1000	V1	3	43	(5.7)		10.4*	-29.9	clear
74	05	17	1230	G1	3	43	(5.7)	(-3.9)	20.7*	-20.0(-161)	turbid
74	05	17	1330	V1	3	43	(5.7)		16.2	-24.5	clear
74	05	21	2200	V1	1	46	(6.1)		[illegible]	-31.3	clear
74	05	22	1500	V1	2	46	(6.1)		11.3	-29.0	clear
74	05	23	1600- 1800	V1	1.2	44	(5.9)		18.4	-22.3	clear
74	05	23	1800- 2000	V2	3	44	(5.9)		9.3	-30.9	clear
74	05	23	1700	R1	3	43	(5.7)		21.8	-19.0	residue
74	05	23	1800	S1	3	40	(5.3)		16.9*	-23.7	clear
74	05	23	1800	S2	3	40	(5.3)		15.1	-25.4	clear
74	05	23	1800	S3	3	40	(5.3)		17.1	-23.4	clear
74	05	23	1800	S4	3	43	(5.7)		18.7	-21.9	clear

continued....

Table B-1, continued:

Sample YR,	MO,	DA,	LDT,	TYPE	Volume Used mls	Pressure CO_2 mm Hg	(kPa)	$\delta^{18}O^{\#}$ $^{o}/_{oo}$	$\delta^{18}O_{SMOW}$ $^{o}/_{oo}$	Sample water comments
74	05	24	1130	V1	1	44	(5.9)	22.3*	-18.5	clear
74	06	03	1600- 2030	V1	3	43	(5.7)	15.0*	-25.5	clear
74	06	03	1400	R1	3	42	(5.6)	24.7*	-16.3	residue
74	06	03	1400	R2	3	42	(5.6)	24.8*	-16.2	residue
74	06	05	1500	V1	3	44	(5.9)	18.3*	-22.3	clear
74	06	05	to	R1	3	43	(5.7)	36.3*	-5.1	residue
74	06	05		R2	3	43	(5.7)	28.9*	-12.2	"
74	06	05	1900	R3	3	43	(5.7)	31.3*	-9.9	"
74	06	06	pm	R1	3	41	(5.5)	24.3	-16.7	"
74	06	08	1515	R1	3	43	(5.7)	21.7*	-19.[illegible]	"
74	07	03	1800	V1	1.8	41	(5.5)	19.8*	-20.9	clear
74	07	04	1730	V1	1.2	41	(5.5)	13.6	-26.8	clear
74	07	04	1900	R1	3	41	(5.5)	24.3	-16.7	"
74	07	04	1900	R2	3	41	(5.5)	22.9	-17.9	turbid
74	07	04	1900	R3	3	41	(5.5)	21.9	-18.9	clear
74	07	04	2000	H1	3	41	(5.5)	21.2	-19.6	turbid
74	07	04	2100	R4	3	41	(5.5)	22.1	-18.7	turbid
74	07	04	2400	H2	3	41	(5.5)	21.1*	-19.7	clear
74	07	04	2400	R5	3	41	(5.5)	20.1*	-20.6	"

continued...

Table B-1, continued:

Sample					Volume Used	Pressure CO_2		$\delta^{18}O^{\#}$	$\delta^{18}O_{SMOW}$	Sample water
YR,	MO,	DA,	LDT,	TYPE	mls	mm Hg	(kPa)	‰	‰	comments
74	07	05	1300-1500	V1	1.2	46	(6.1)	12.1*	-28.3	clear
74	07	05	1600-2000	V2	1.4	46	(6.1)	14.2*	-26.2	"
74	07	05	1730	R1	2	150	(20.0)	24.7	-15.0	"
74	07	05	2027	R2	2	150	(20.0)	29.7	-10.8	"
74	07	05	2047	R3	2	155	(20.7)	--		"
74	07	05	2131	H1	2	155	(20.7)	25.1	-15.4	turbid
74	07	05	2155	H2	2	155	(20.7)	24.2	-16.3	"
74	07	05	2342	H3	2	155	(20.7)	23.3	-17.2	"
74	07	05	2348	R4	2	155	(20.7)	23.4	-17.1	"
74	07	06	1745	R1	-	-	-	-	-	-
74	07	07	1700	R1	2	155	(20.7)	24.0	-16.5	turbid
74	07	09	0926-1247	V1	2	155	(20.7)	20.7	-19.8	clear
74	07	09	1323-1500	V2	2	155	(20.7)	20.3	-20.2	"
74	07	09	2043	H1	2	155	(20.7)	23.1	-17.4	residue
74	07	09	2205	R1	2	155	(20.7)	27.8	-12.7	turbid
74	07	09	2225	H2	2	153	(20.4)	23.5	-17.0	residue
74	07	10	1530-1730	V1	2	153	(20.4)	15.6	-24.9	clear

continued...

Table B-1, continued:

Sample					Volume Used	Pressure CO_2		$\delta^{18}O^{\#}$	$\delta^{18}O_{SMOW}$	Sample water
YR,	MO,	DA,	LDT,	TYPE	mls	mm Hg	(kPa)	‰	‰	comments
74	07	11	1512-1650	V1	2	155	(20.7)	17.4*	-23.1	clear
74	07	11	1630	R1	2	155	(20.7)	27.7	-12.8	"
74	07	11	1630	R2	2	155	(20.7)	28.6	-11.9	"

[#] These δ values are relative to local standard. No asterisk and asterisk (*) on measured values denotes a standard deviation ≤ 0.1 and ≤ 0.2 units, respectively. In parenthesis are the measured values of δD.

Table B-11

Isotopic Analyses of Vapour and Precipitation Samples Collected During 1975.

Sample					Volume Used	Pressure CO_2		$\delta^{18}O^{\#}$	$\delta^{18}O_{SMOW}$	Sample water
YR,	MO,	DA,	LDT,	TYPE	mls	mm Hg	(kPa)	°/oo	°/oo	comments
75	05	13	1450 to	V1	2	150	(20.0)	13.6	-28.1	clear
75	05	13	1730	V2	2	150	(20.0)	14.0	-27.7	"
75	05	15	1015 to	V1	2	150	(20.0)	14.1	-27.7	turbid
75	05	15	1300	V2	2	150	(20.0)	14.3	-27.5	"
75	05	16	1045 to	V1	2	170	(22.7)	15.1	-26.6	clear
75	05	16	1330	V2	2	170	(22.7)	13.5	-28.2	"
75	06	12	1400	V1	2	170	(22.7)	11.2	-30.5	turbid
75	06	16	1200-1545	V1	2	170	(22.7)	12.3	-29.5	clear
75	06	16	1910	R1	2	170	(2217)	27.5*	-14.2	"
75	06	16	1838	R2	2	170	(22.7)	22.9	-18.8	"
75	06	16	1838	H1	2	170	(22.7)	22.9	-20.1	"
75	06	16	1850	H2	2	170	(22.7)	21.6	-	residue
75	06	17	1430	V1	2	170	(22.7)	15.1	-26.6	clear
75	06	17	1450	R1	2	170	(22.7)	23.1	-18.4	residue

continued...

Table B-II, continued:

Sample					Volume Used	Pressure CO_2		$\delta^{18}O^{\#}$	$\delta^{18}O_{SMOW}$	Sample water
YR,	MO,	DA,	LDT,	TYPE	mls	mm Hg	(kPa)	$^{o}/_{oo}$	$^{o}/_{oo}$	comments
75	06	18	1030	V1	2	170	(22.7)	13.5	-28.2	clear
75	06	18	1245	V2	1.7	170	(22.7)	19.4	-22.3	"
75	06	18	1500	V3	2	170	(22.7)	13.2	-28.5	"
75	06	18	1730	V4	2	170	(22.7)	10.6	-31.1	"
75	06	19	1645	V1	2	170	(22.7)	14.3	-27.4	"
75	06	20	1220- 1320	V1	2	155	(20.7)	15.1	-26.6	"
75	06	20	1442	RG1	2	155	(20.7)	23.9	-17.8	residue
75	06	20	1442	G1	2	155	(20.7)	20.9	-20.8	"
75	06	20	1442	R2	2	155	(20.7)	20.5	-21.2	clear
75	06	20	1450	R3	2	155	(20.7)	22.5	-19.2	"
75	06	21	1148 to	V1	1	104	(13.9)	15.4	-26.3	"
75	06	21	1432	V2	2	155	(20.7)	22.7	-19.0	"
75	06	21	1530	R1	2	155	(20.7)	22.4	-19.3	residue
75	06	21	1610	R2	2	155	(20.7)	30.4	-11.3	"
75	06	21	2100	R3	2	155	(20.7)	25.6	-16.2	clear
75	06	25	[illegible]40	G1	2	101	(13.5)	23.8	-17.9	residue
75	06	28	1140	G1	1	133	(17.7)	18.1	-23.6	"

continued...

Table B-11, continued:

Sample					Volume Used	Pressure CO_2		$\delta^{18}O^{\#}$	$\delta^{18}O_{SMOW}$	Sample water
YR,	MO,	DA,	LDT,	TYPE	mls	mm Hg	(kPa)	°/oo	°/oo	comments
75	07	03	1202- 1342	V1	-	-	-	-	-	-
75	07	03	1702	R1	2	155	(20.7)	36.4	-5.3	clear
75	07	03	1800	R2	2	155	(20.7)	37.8	-3.9	"
75	07	03	2005	R3	-	-	-	-	-	
75	07	03	2005	G1	2	155	(20.7)	31.0	-10.8	residue
75	07	03	2020	G2	2	155	(20.7)	28.4	-13.3	"
75	07	03	2145	G3	2	155	(20.7)	29.2	-12.5	"
75	08	05	1154- 1500	V1	2	104	(13.9)	23.7	[illegible]0	clear
75	08	05	1637	R1	2	104	(13.9)	31.7	-10.0	residue
75	08	05	1747	G1	0.9	104	(13.9)	48.5	+6.8	"
75	08	05	1748	RG2	2	104	(13.9)	27.4	-14.3	"
75	08	05	1753	G3	2	104	(13.9)	24.1	-17.6	"
75	08	06	1338	R1	2	111	(14.8)	27.2	-14.5	residue
75	08	06	1338	G1	2	111	(14.8)	28.4	-13.3	"
75	08	06	1345	G2	1	111	(14.8)	27.7	-14.0	"
75	08	06	1353	G3	2	111	(14.8)	29.8	-12.5	"
75	08	28	1502	R1	2	116	(15.5)	29.2	-12.5	residue
75	08	28	1528	R2	2	116	(15.5)	36.0	-5.7	"
75	08	28	1648	R3	2	116	(15.5)	29.0	-12.7	"
75	08	28	1744	R4	2	116	(15.5)	37.4	-4.3	"
75	08	28	1750	R5	2	104	(13.9)	29.3	-12.4	"
75	08	28	1915	G1	2	104	(13.9)	26.9	-14.8	"

[#] These δ values are relative to local standard. No asterisk and asterick (*) on measured values denotes a standard deviation ≤ 0.1 and ≤ 0.2 units, respectively.

Table B-III

Isotopic Analyses of Vapour and Precipitation Samples Collected During 1976

Sample					Volume Used	Pressure CO_2		$\delta^{18}O^{\#}$	$\delta^{18}O_{SMOW}$	Sample water
YR,	MO,	DA,	LDT,	TYPE	mls	mm Hg	(kPa)	$^{o}/oo$	$^{o}/oo$	comments
76	03	12		S2	2	108	(114.4)	15.7	-26.0	residue
76	03	12		S3	2	108	(114.4)	17.4	-24.3	"
76	03	12		S4	2	108	(14.4)	19.1	-22.6	"
76	03	12		S5	2	108	(14.4)	18.5	-23.2	"
76	06	15	1439	V1	1.9	108	(14.4)	10.8	-30.9	clear
			to							
76	06	15	1613	V2	1.2	99	(13.2)	8.6	-33.1	"
76	06	17	1015	V1	2	99	(13.2)	15.0	-26.7	"
76	06	17	1015	V2	2	99	(13.2)	12.7	-29.0	"
76	06	18	0912	V1	2	99	(13.2)	14.5	-27.3	turbid
76	06	18	0912	V2	2	99	(13.2)	18.1	-23.6	"
76	06	18	a.m.	V2	2	99	(13.2)	13.8	-28.0	"
76	06	19	1700	G1	2	99	(13.2)	19.4	-22.3	residue
76	06	19	1730	G2	2	99	(13.2)	21.0	-20.7	"
76	06	19	1750	R1	2	98	(13.1)	20.8	-20.9	"
76	06	19	p.m.	G3	2	99	(13.2)	21.9	-19.8	clear
76	06	19	p.m.	G4	2	98	(13.1)	21.8	-19.9	"
76	06	21	0745	V1	2	98	(13.1)	14.0	-27.7	"
76	06	21	0745	V2	2	98	(13.1)	14.9	-26.8	"
76	06	21	1400	V3	2	98	(13.1)	13.3	-28.4	"

continued...

Table B-111, continued:

Sample					Volume Used	Pressure CO_2		$\delta^{18}O^{\#}$	$\delta^{18}O_{SMOW}$	Sample water
YR,	MO,	DA,	LDT,	TYPE	mls	mm Hg	(kPa)	$^{o}/_{oo}$	$^{o}/_{oo}$	comments
76	06	30	1020 to 1230	V1	2	98	(13.1)	18.9	-22.8	clear
76	06	30	1307	V2	2	105	(14.0)	19.2	-22.5	"
76	06	30	1330	V3	2	105	(14.0)	32.2	-9.5	"
76	06	30	1600	V4	2	105	(14.0)	21.5	-20.2	"
76	07	08	1330-1430	V1	2	106	(14.1)	16.4	-25.3	"
76	07	08	1430-1520	V2	2	106	(14.1)	17.1	-24.6	"
76	07	08	1600	V3	2	106	(14.1)	18.5	-23.2	"
76	07	08	1602	V4	2	106	(14.1)	18.7	-23.0	"
76	07	08	1800	V5	2	106	(14.1)	14.5	-27.2	"
76	07	08	1801	V6	2	106	(14.1)	16.1	-25.6	"
76	07	08	1802	V7	2	97	(12.9)	16.6	-25.1	"
76	07	08	1606	R1	2	97	(12.9)	29.7	-12.0	"
76	07	08		R2	2	97	(12.9)	26.8	-14.9	"
76	07	08	to	R3	2	97	(12.9)	26.2	-15.5	"
76	07	08		R4	2	97	(12.9)	26.2	-15.5	"
76	07	08	1700	R5	2	97	(12.9)	26.9	-14.8	"
76	07	08	1804	R6	2	102	(13.6)	30.4	-11.3	"
76	07	08	1810	R7	2	102	(13.6)	28.8	-12.9	"
76	07	08	1820	R8	2	102	(13.6)	28.7	-13.0	"
76	07	08	1850	G1	0.3	102	(13.6)	23.2	-18.5	residue

continued...

Table B-III, continued:

Sample					Volume Used	Pressure CO_2		$\delta^{18}O^{\#}$	$\delta^{18}O_{SMOW}$	Sample water
YR,	MO,	DA,	LDT,	TYPE	mls	mm Hg	(kPa)	°/oo	°/oo	comments
76	07	13	0827	V1	2	109	(14.5)	17.1	-24.6	clear
			to							
76	07	13	0947	V2	2	109	(14.5)	17.4	-24.3	"
76	07	13	0955	V3	2	109	(14.5)	17.0	-24.7	"
			to							
76	07	13	1145	V4	2	109	(14.5)	17.7	-24.0	"
76	07	14	1130	V1	2	109	(14.5)	14.5	-27.2	"
			to							
76	07	14	1300	V2	2	114	(15.2)	14.0	-27.7	"
76	07	14	1303	V3	2	114	(15.2)	14.3	-27.4	"
			to							
76	07	14	1421	V4	2	114	(15.2)	13.9	-27.8	"
76	07	14	1400	R1	2	109	(14.5)	24.5	-17.2	residue
76	07	15	0900	V1	2	114	(15.2)	13.5	-28.2	clear
			to							
76	07	15	1055	V2	2	114	(15.2)	13.1	-28.6	"
76	07	15	1114	V3	2	114	(15.2)	14.5	-27.2	"
76	07	15	1239	V4	2	105	(14.0)	14.7	-27.0	"
76	07	21	p.m.	H1	2	105	(14.0)	24.4	-17.3	residue
76	07	21	p.m.	H2	1.8	105	(14.0	22.7	-19.0	"
76	07	21	p.m.	RH4	2	105	(14.0)	23.7	-18.0	clear
76	07	21	p.m.	RH5	2	105	(14.0)	23.2	-18.5	"
76	07	21	p.m.	RH6	2	105	(14.0)	22.5	-19.2	"

[#] These δ values are relative to local standard. No asterisk and asterisk (*) on measured values denotes a standard deviation ≤ 0.1 and ≤ 0.2 units, respectively.