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ON A RELATIONSHIP BETWEEN AIR TEMPERATURE AND OXYGEN ISOTOPE RATIO OF SNOW AND FIRN IN THE SOUTH POLE REGION

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During the period November 1964 to October 1965 a total of 89 samples of precipitation were collected at the Amundsen-Scott Station. Oxygen isotopes analysis discloses the presence of an 'isotopic summer' and an 'isotopic winter'. These results combined with upper air observation permit the formulation of a relationship between δ_{OX} of precipitation and the temperature of an effective condensation level. A simple model based on equilibrium Rayleigh condensation processes for moist air masses over Antarctica is advanced.

1. INTRODUCTION

Many investigations have established that there is a correlation between $^{18}O/^{16}O$ and D/H ratios of precipitations and the temperature of the air which explains the observed variations of δ_{OX} with season, altitude and latitude. See bibliography [1, 2].

The theoretical background for the applications of this parameter [3-5] is developed within the framework of equilibrium Rayleigh condensation processes in effect during the cooling of a moist air mass originating over the ocean and followed by condensation under conditions which are either isobaric, adiabatic or both.

Antarctica is particularly suited for these studies as the original sequence of deposition of precipitations appears not to be severely altered.

A firmer footing on the glaciological and climatological implications of stable isotope profiles from firn would be gained if it were possible to find the relationship between the isotopic composition of the snow and the meteorological environment at the time of precipitation, together with the degree of alteration of the original isotopic composition of firn due to metamorphic processes acting on it.

2. FIELD AND LABORATORY WORK

Earlier investigations [6-8] have produced valuable results, while simultaneously indicating the need for further work. We present here additional data which have been obtained by performing oxygen isotope analyses on 89 samples of freshly fallen snow, taken by one of us (L.A.) during the period November 1964

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to October 1965 at Amundsen-Scott Station. Every month is represented by one or more samples.

Extreme care was taken to secure samples uncontaminated by drifting snow. The collecting area was a sheltered wooden platform of about 10 m^2 area raised about half a meter above the snow surface and kept clean by frequent brooming. After the collection was taken, the sample was handled so as to minimize evaporative losses. As soon as the snow was melted, the liquid water was poured into 100 cm^3 plastic bottles and sealed with wax.

The snow morphology, surface meteorological conditions and upper air data pertaining to the sampled period were recorded (see table 1). A low wind situation was necessary to obtain samples uncontaminated by drifting snow. On meteorological grounds it is felt that no significant bias was introduced by sampling under such restricted meteorological conditions.

Isotopic analyses on samples of well dated firn taken in the immediate vicinity of Amundsen-Scott Station were also carried out [9]. The results obtained are in agreement with earlier published profiles [10].

The $^{18}O/^{16}O$ ratios were measured with a spectrometer equipped with a double collector and a double gas inlet system. The experimental procedures were essentially the same as those described by Epstein and Mayeda [3]. The results reported here are corrected for the various factors discussed by Craig [11]. They are expressed in terms of relative deviation per mil as follows:

$$\delta_{ox} = \frac{^{18}O/^{16}O(\text{sample}) - ^{18}O/^{16}O(\text{SMOW})}{^{18}O/^{16}O(\text{SMOW})} \times 10^3 ,$$

where SMOW stands for standard mean ocean water [12]. The reproducibility of the present measurements is better than 0.3‰.

3. THE δ_{ox} VALUES OF SNOW VERSUS TIME OF COLLECTION

A scatter diagram (fig. 1) shows the δ_{ox} values of freshly precipitated snow against time of collection. The points are readily grouped into an 'isotopic summer' and an 'isotopic winter' with average δ_{ox} respectively of −44 and −58. The transition from one to the other is fast during fall. The lack of samples obscures the rate of return to summer conditions.

The twelve months unweighted average is δ_{ox} = −52 and the extremes −63 and −33. It is noted in passing that −63 is the lowest value of δ_{ox} ever measured for natural precipitations.

4. THE δ_{ox} VALUES IN FIRN

From an inspection of the published profiles for firn at Amundsen-Scott Station, the following features of interest to the present work are noted:

1) For every year represented in the accumulation record, there is a high and low in the δ_{ox} values.

2) The amplitude of the δ_{ox} oscillations in firn is bracketed by the extreme values of the 1964/1965 precipitations. This fact already noted at King Baudouin Base by Gonfiantini, Togliatti, Tongiorgi, De Breuck and Picciotto [13] may be partly the consequence of the unavoidable smoothing introduced while sampling the firn and partly the result of mixing processes by the wind at the surface.

3) The overall mean of the δ_{ox} values for all the profiles is −51, close to the unweighted average of the precipitation δ_{ox} values. The mean δ_{ox} value of the firn taken over several years seems to be representative of the mean δ_{ox} value of the fresh snow at the South Pole. It appears that δ_{ox} values of the precipitations are not, in this case, significantly altered by metamorphic processes acting in the firn during the time span covered by the sampling. Nevertheless, the existence of some degree of enrichment in depth-hoar layers cannot be ruled out. In such carefully sampled layers we have in fact found systematically high δ_{ox} values, in agreement with previous observations [10].

5. OXYGEN ISOTOPIC COMPOSITION OF PRECIPITATIONS AND THEIR TEMPERATURE OF FORMATION

At the South Pole, the determination of the temperature at which the snowfall originates is difficult because the humidity profile from the radiosonde records is unreliable on account of the prevailing low temperatures. Likewise, the balloon disappearance method to obtain the cloud base height is not often

Table 1
Oxygene isotope ratio of precipitations at Amundsen-Scott Station and temperature of the air deduced from the concurrent radiosonde sounding.

Sample	Date	Surface †	Temperature (−°C)			Max	δ_{ox} (−‰)
			650 mb	600 mb	500 mb		
1	Nov. 21	33	28.5	30.0	38.0	28	49.9
2	22	34					52.7
3	22	34	30.0	32.5	38.0	30	47.3
4	23	38	28.5	32.0	41.0	28	47.2
5	23	NR					43.3
6	24	34				NS	46.3
7	Dec. 1	32	31.5	35.0	40.5	31	40.7
8	7	30	34.0	34.0	39.0	NI	32.5
9	8	30	30.0	33.0	38.5	29	47.9
10 *	9	30					47.9
11	15	25	33.0	33.0	37.0	NI	43.5
12	21	23	24.5	28.0	37.0	NI	49.1
13	23	27	30.5	33.5	39.5	NI	41.9
14	23	27					47.3
15	24	27				NS	38.2
16	24	NR				NS	42.4
17	25	29	28.5	31.5	39.5	27	34.3
18 *	28	27					48.0
19	Jan. 1	27	31.0	33.0	39.5	NI	42.9
20	2	29	32.5	32.0	37.5	NI	41.3
21	5	24	25.0	27.5	29.5	NI	38.6
22	7	23				NS	39.4
23	12	25				NS	37.1
24 *	16	24				NS	46.5
25	22	28				NS	50.1
26	24	30				NS	46.3
27 *	28	34				NS	48.4
28	Feb. 4	30-34	29.0	30.0	36.5	28	43.4
29	11	35					46.0
30	11	34	27.5	28.5	37.5	27 **	41.5
31	11	34					39.2
32	12	36	29.0	29.5	37.0	28	40.8
33	13	39	30.5	32.0	38.5	31	48.7
34	18	40-34				NS	43.4
35	18	34				NS	42.9
36	19	42				NS	41.3
37	20	41				NS	43.0
38	21	42				NS	46.1
39	24	43				NS	48.4
40	24	45				NS	47.8
41	Mar. 10	43	32.0	28.0	36.0	28	49.4
42	16	44	31.0	30.5	38.0	29 **	45.7
43 *	17	48					51.1
44	26	64	43.5	40.0	46.0	39	55.8
45	26	65	43.0	39.5	44.5	39	57.0
46	27	63-60				NS	57.3
47	30	47	41.5	36.0	42.5	36 **	57.9

Table 1 (continued)

Sample	Date	Surface †	Temperature (−°C)			Max	δox (−‰)
			650 mb	600 mb	500 mb		
48	Apr. 14	50	38.0	27.5	34.0	27	44.5
49	14	33-37	21.0	23.0	32.0	21	40.3
50	15	38-43					41.9
51	19	54	37.0	35.0	42.0	33	53.8
52	May 4	57	38.0	35.0	39.0	35	57.1
53	5	52-47					50.4
54	5	47					53.0
55	5	46	34.5	30.5	41.0	30 **	52.2
56 *	10	64					61.9
57	28	47	28.0	30.5	38.5	28	48.8
58	June 2	49	39.5	36.0	43.5	35	56.8
59	2	49					55.3
60	3	53					55.8
61 *	3	53					54.9
62	3	48					61.6
63	3	46	35.5	35.5	41.5	35 **	58.2
64	4	42					62.8
65	4	41-54	38.5	40.0	45.0	38	60.7
66	7	58	39.5	38.0	42.0	37	59.5
67	7	57-63	39.0	40.0	45.5	38	62.7
68	9	59-51	41.0	37.0	41.5	37	55.0
69	9	49					53.9
70	9	45	32.0	32.0	39.5	29 **	53.9
71	10	49					54.5
72	10	47	40.0	42.0	45.0	39	53.0
73	12	49-54					54.6
74	12	49	32.0	31.0	39.0	31 **	54.0
75	14	53					58.0
76	14	53	43.5	35.5	42.0	35 **	54.0
77	15	54				NS	49.0
78	July 10	67-55	34.0	34.0	39.0	33 *	57.3
79	11	52				NS	55.4
80	13	65					55.4
81	13	62	38.5	38.0	43.5	37	54.2
82	Aug. 14	67	48.0	38.0	46.5	37	58.6
83	15	61					58.7
84	15	58	44.5	43.5	50.0	43	56.1
85	15	52	34.5	35.0	43.5	34	51.7
86	Sep. 23	47					50.0
87	23	46	33.0	31.5	40.0	30 *	54.3
88 *	Oct. 8	58					61.5
89 *	9	57					61.4

* = accretion collection.
** = temperature of balloon measured cloud base.
NI = no inversion.
NS = no sounding.
NR = not recorded.
† = temperature at the surface during the period of precipitation.

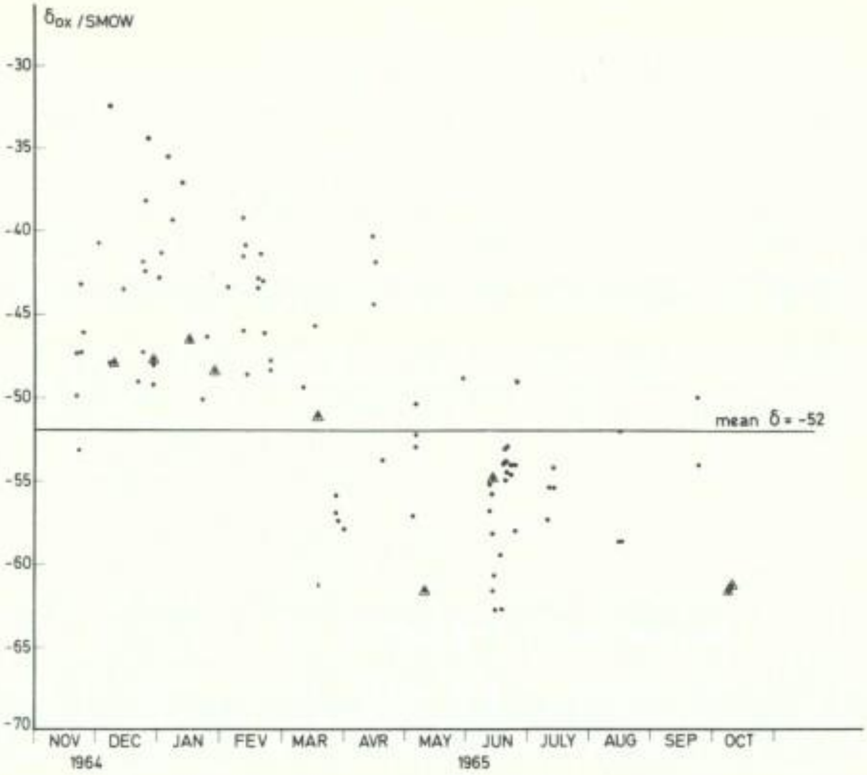

Fig. 1. The oxygen isotope ratio of precipitations versus their time of occurrence.

applicable either due to the lack of sharp cloud boundaries.

In fig. 2, the δ_{ox} value of every sample appears plotted together with the observed range of temperatures taken from the concurrent radiosonde sounding. The 500 millibars level was chosen as the upper boundary of the precipitating layer because the contribution of the remainder of the troposphere should be negligible on account of its low moisture content.

If a unique relation between δ_{ox} and the air temperature exists which simultaneously satisfies our set of values, the graphical representation must be contained within the stippled area shown in fig. 2. This area is the locus of all the effective condensation level temperatures, for each precipitation period, because they must lie between the temperature extremes found during each particular radiosonde sounding.

Outside of this region, any other δ_{ox} versus air temperature relationship will give effective condensation level temperatures only for a lesser number of precipitation periods. In other words, such a relationship may be applicable only to a restricted climatological period, instead of representing conditions throughout the year.

In our case, the desired relation can, tentatively, be represented by line A which has the equation:

$$\delta_{ox} = 1.4\, t\,(^{\circ}\mathrm{C}) + 4.0\,. \qquad (1)$$

For each precipitation, an effective condensation temperature may be obtained from this equation, and, from the radiosonde profile, the corresponding condensation level height. It appears that the clouds form at a higher level in summer than in winter, which is in agreement with the climatological records [14] for Amundsen-Scott Station.

The existence of such a relationship embracing the majority of our observations, lends support to the likely assumption that, on the average, the moist air masses reaching the South Pole region have a common origin of relatively constant temperature the whole year through.

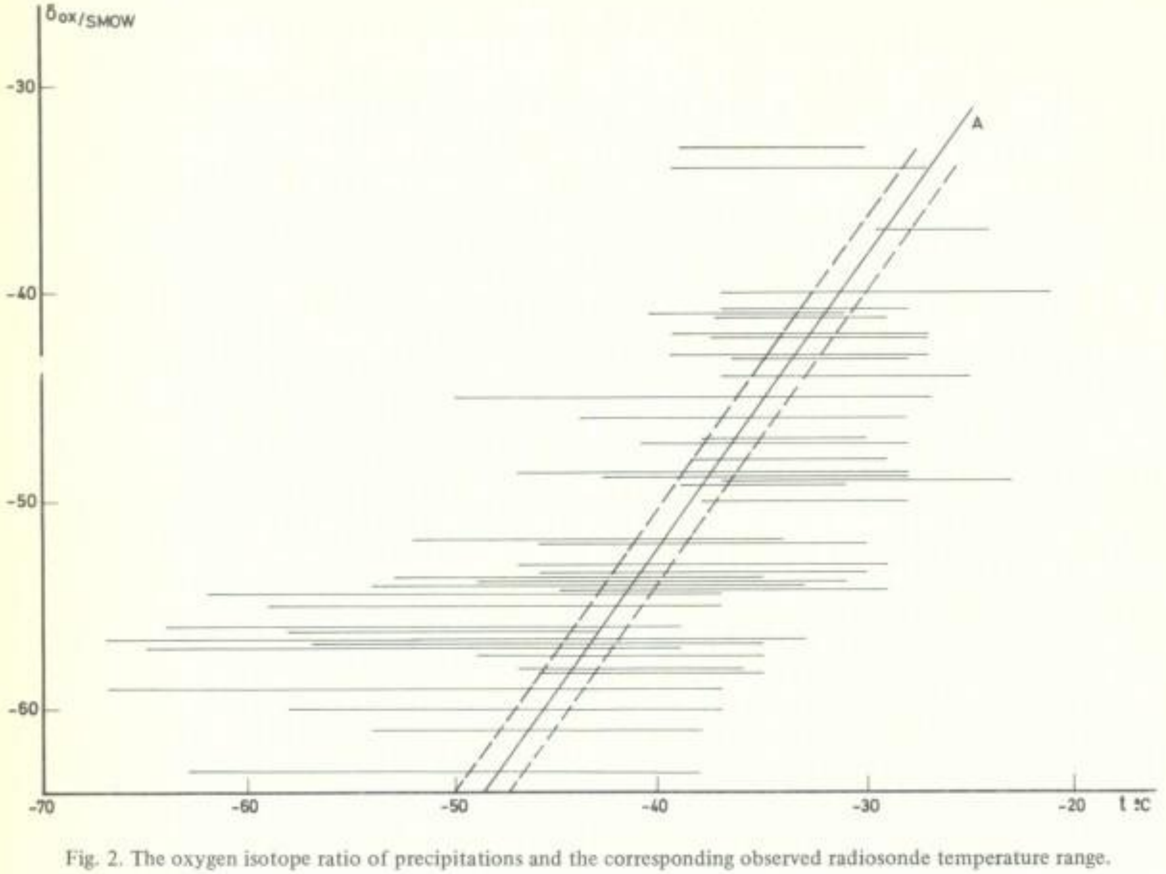

Fig. 2. The oxygen isotope ratio of precipitations and the corresponding observed radiosonde temperature range.

This assumption and the use of equilibrium Rayleigh condensation processes for the evolution of moist air masses penetrating the Antarctic region permit the development of the following simple model for the observed oxygen isotope ratios of the precipitations.

The above stated relationship of δ_{ox} versus t(°C) for the Amundsen-Scott Station and a similar one for King Baudouin Base [6] are the only ones available for the whole year in Antarctica.

At King Baudouin Base, the mean δ_{ox} of firn is −22 which corresponds to a mean annual temperature for the effective condensation level of −17°C. Similar parameters for Amundsen-Scott Station are $\delta_{ox} = -51$ and $t = -39$°C. A good fit to these datum points is obtained by assuming that moist air initially in equilibrium with ocean water at approximately 10°C cools isobarically (at 1000 mb) to −5°C and then undergoes adiabatic expansion.

The calculated oxygen isotope ratios for precipitation resulting from this model, together with the temperature, pressure and elevation of the mean condensation levels are reported in table 2. The latitudes corresponding to these temperatures are also given.

In view of the lack of a direct determination of the isotopic fractionation factor α_{ox} at the low temperature encountered in Antarctica, the α_D as measured by Merlivat and Nief [15] were used and subsequently the δ_D values obtained were converted into δ_{ox} values by using the empirical relation of Epstein, Sharp and Gow [10].

Fig. 3 gives the oxygen isotope ratio versus the temperature of the effective condensation level for Antarctic precipitations. Curve 1 is calculated as stated before. For comparison purposes, curve 2 was drawn after computing of δ_{ox} with the α_{ox} values deduced from the Zhavoronkov, Uvarov and Sevryugova [16] formula extended to the present range of

Table 2

Main features pertaining to the determination of the oxygen isotope ratio versus temperature of effective condensation level relationship for Antarctic precipitations.

Process	Mean effective condensation level			Calculated δ_{ox} for precipitation	Latitude (^{o}S)
	Pressure (mb)	Elevation a.s.l. (m)	Temperature (^{o}C)		
Evaporation over ocean	1000	0	+10	0	45 (ref. [17])
Isobaric cooling	1000	0	−5	−10	65 (ref. [17])
Adiabatic cooling (ice)	800	1500	−17	−22	70 (King Baudouin Base)
Adiabatic cooling (ice)	600	3700	−35	−51	90 (Amundsen-Scott Station)
Adiabatic cooling (ice)	550	4350	−41	−60	90

temperature (although this extrapolation lies well outside of the experimental values). These two curves are calculated starting from the δ_{ox} and t^{o} mean values for King Baudouin Base precipitations (line B).

It is apparent that line A, derived empirically in the present work, lies in between the two calculated curves. The slopes of these three curves agree rather well.

As far as absolute values are concerned, starting from the measured values at the coastal station, the proposed moist air evolution produces δ_{ox} values for

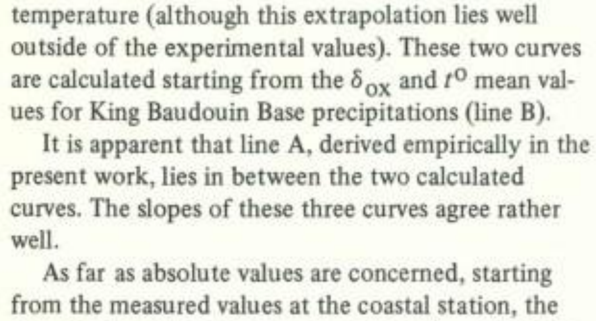

Fig. 3. The oxygen isotope ratio versus the temperature of the effective condensation level for Antarctic precipitations.
Curve A (empirical) for Amundsen-Scott Station.
Curve B (empirical) for King Baudouin Base.
Curve 1 and 2 (computed).

the Plateau region comparable with those found by direct measurement.

It is somewhat surprising that this simple model agrees as well as it does not only with the measured δ_{ox} values but also with the latitudinal position of a reasonable source for the water vapor. The derived initial temperature of +10^{o}C corresponds to a latitude of 45^{o}S [17], north of the circumpolar cyclonic belt which is centered, on the average, in the vicinity of 60^{o}S.

Friedman, Redfield, Schoen and Harris [1] deduce from their model that the source of water for the precipitations at King Baudouin Base is at +5^{o}C in winter and +15^{o}C in summer, in general agreement with our value, although they assume the cooling of the moist air to be produced only by an isobaric process.

As pointed out by Dansgaard ([2] and private communication) the δ_{ox} values of precipitations over the ocean are close to zero only in equatorial regions; they could be as low as −8‰ at latitudes around 50^{o}S, due to exchange and uptake of new vapor over the ocean. The origin of water vapor in the proposed model would consequently move towards higher latitudes, still remaining plausible.

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