

## ESTIMATING RATIOS OF SNOW ACCUMULATION IN ANTARCTICA BY CHEMICAL METHODS

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**ABSTRACT.** Snow and firn samples from 2 and 5 m deep pits were analyzed for seven sites on the Ross Ice Shelf, Antarctica. Na, Mg, Ca, and K concentrations change with depth, the range of concentrations being approximately 10 : 1 for all four elements. The changes in concentrations for the four elements at any one site are highly correlated, suggesting that the impurities are introduced into the snow-pack simultaneously by the same mechanisms.

Pronounced periodic structure of the vertical chemical profiles leads to strong correlations ( $\gamma > 0.9$ ) of the chemical features from site to site separated by distances up to 440 km.

Assuming that the observed chemical features are periodic as a function of depth due to temporal variations caused by large-scale phenomena, then the wavelength (in depth) of these features should be proportional to the accumulation. Under the assumptions, the linear regression ratio of one site to another will give the relative accumulations at these sites. The ratios of snow accumulation estimated by these chemical methods agree, within a few per cent, with the ratios for the same sites estimated by total  $\beta$ -activity or stratigraphic methods.

It is suggested that the chemical variations with depth are caused by meteorological events which may have seasonal changes in frequency and intensity. It is also suggested that the most-favored season for the production of chemical-concentration maxima is autumn because of the documented higher frequency of precipitating storms on the Ross Ice Shelf and the minimum in sea-ice extent at that time of year.

**RÉSUMÉ.** L'estimation des taux d'accumulation de la neige en Antarctique par des méthodes chimiques. On a analysé des échantillons de neige et glace issus de carottages à 2 et 5 m de profondeur en sept sites du Ross Ice Shelf en Antarctique. Les concentrations en Na, Mg, Ca et K varient avec la profondeur, le rapport des concentrations extrêmes étant approximativement de 10 pour 1 pour tous ces éléments. Les variations des concentrations pour les quatre éléments en un site sont étroitement corrélées, ce qui suggère que les impuretés proviennent des mêmes causes.

De fortes corrélations temporelles (avec des coefficients de corrélation supérieurs à 0,9) existent entre les variations chimiques d'un site à un autre séparé par des distances allant jusqu'à 440 km.

Comme les rapports des profondeurs des particularités chimiques en différents sites sont semblables aux rapports entre les accumulations de neige à ces mêmes sites, on peut utiliser les variations chimiques pour estimer les accumulations relatives. Les taux d'accumulation de la neige estimés par ces résultats chimiques concordent à quelques pour cent près, avec les taux d'accumulation dans les mêmes sites estimés grâce à la radiation  $\beta$  totale ou par des méthodes stratigraphiques.

On émet l'hypothèse que les variations chimiques avec la profondeur ont pour origine des événements météorologiques qui peuvent avoir des variations saisonnières en fréquence et en intensité. La saison la plus favorable pour la production des concentrations chimiques maximum est l'automne en raison de la plus forte fréquence de perturbation avec précipitations sur le Ross Ice Shelf et de l'extension minimum de la glace de mer à cette époque de l'année.

**ZUSAMMENFASSUNG.** Abschätzung der Schneeauftragsraten in der Antarktis mit chemischen Methoden. Für sieben Stellen auf dem Ross Ice Shelf, Antarktika, wurden Schnee- und Firnproben aus Schächten von 2 und 5 m Tiefe analysiert. Na-, Mg-, Ca- und K-Konzentrationen verändern sich mit der Tiefe, wobei der Konzentrationsbereich für alle 4 Elemente etwa 10 : 1 beträgt. Unter der Annahme, dass die Verunreinigungen gleichzeitig und auf die gleiche Weise in die Schneedecke gelangen, erweisen sich die Konzentrationsschwankungen der vier Elemente an den einzelnen Stellen als stark korreliert.

Hohe zeitliche Korrelationen (Korrelationskoeffizienten  $> 0,9$ ) bestehen zwischen den chemischen Veränderungen von Probeorten, die bis zu 440 km voneinander entfernt liegen.

Unter der Annahme, dass die beobachteten chemischen Erscheinungen infolge zeitlicher Schwankungen, hervorgerufen durch großflächige Einwirkungen, periodisch mit der Tiefe verlaufen, sollte die vertikale Wellenlänge dieser Erscheinungen proportional zur Akkumulation sein. Dann liefert das lineare Regressionsverhältnis zwischen zwei Stellen die relativen Akkumulationen an diesen Stellen. Die mit diesen chemischen Methoden abgeschätzten Schneeauftragsverhältnisse stimmen innerhalb weniger Prozent mit den Verhältnissen an denselben Stellen überein, die aus der Gesamt- $\beta$ -Aktivität oder mit stratigraphischen Methoden abgeschätzt wurden.

Es wird vermutet, dass die chemischen Veränderungen mit der Tiefe durch meteorologische Ereignisse verursacht sind, deren Frequenz und Stärke jahreszeitlich schwankt. Für die Erzeugung maximaler chemischer Konzentrationen dürfte der Herbst die günstigste Jahreszeit sein, da nach sicheren Beobachtungen in dieser Zeit die Häufigkeit von Stürmen mit Niederschlag auf dem Ross Ice Shelf höher ist und das Meereis seine geringste Ausdehnung besitzt.



## INTRODUCTION

During the International Geophysical Year, studies were made of the snow accumulation on the Ross Ice Shelf, Antarctica, by Crary and others (1962). A large number of sites were located on the ice shelf and stratigraphic methods, supplemented by stake measurements in the north-western areas, were used for making the accumulation determinations.

Warburton and Linkletter (1977) showed that there were close correlations between chemical features in snow-depth profiles measured at several sites on the Ross Ice Shelf, and suggested that the ratios of depths of the chemical features at different sites were similar to the ratios of accumulation at these sites as determined by Crary and others. This was documented further by Warburton and Linkletter (1978), and Warburton and others (1981). Clausen and Dansgaard (1977) sampled a substantial number of locations in the north-western section of the Ross Ice Shelf and have documented accumulation estimates for 36 sites covering an area of approximately 100 000 km<sup>2</sup>. These estimates, based upon total  $\beta$ -activity measurements using snow-pit samples and the 1954–55, 1964–65, and 1970–71  $\beta$ -activity horizons, indicated that accumulation at these sites was generally less by about 50% than previously estimated.

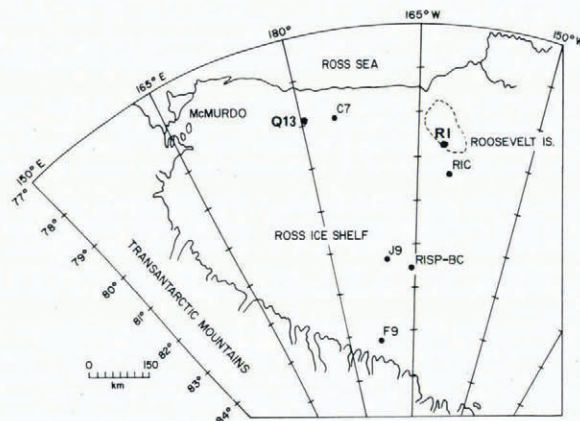


Fig. 1. Ross Ice Shelf, Antarctica. Showing sites of 2 m pits.

Herron and Langway (1979) have reported on the estimated accumulations at three sites on the Ross Ice Shelf (C7.1, Roosevelt Island dome, and J9) based upon variations in the sodium concentrations with depth at each site (Fig. 1). On the assumption that the variations are annual–seasonal, they concluded that the accumulation at C7 is 130 kg m<sup>-2</sup> year<sup>-1</sup>, in good agreement with stake measurements by Heap and Rundle (1964) but 30% less than the estimate of Crary and others. At Roosevelt Island dome, the chemically derived accumulation was 160 kg m<sup>-2</sup> year<sup>-1</sup>, in good agreement with the general accumulation pattern of Bull (1971). At J9 the estimate of 90 kg m<sup>-2</sup> year<sup>-1</sup> is in good agreement with the fission-product derived value of Clausen and Dansgaard (1977).

## FEATURES OF ROSS ICE SHELF STUDY REGION

The Ross Ice Shelf (Fig. 1) was chosen as a region of Antarctica devoid of large orographic features, where the temporal and spatial variations of the chemical composition of the snow deposited on the ice shelf could be investigated. It is approximately triangular in map view and measures about 700 km on a side. It averages about 280 m in thickness with essentially flat surface topography. The only major feature on the ice shelf in the vicinity of the study area is Roosevelt Island, which is approximately 350 m in height above the flat surface



surrounding it. The ice shelf's seaward margin is marked by an abrupt ice cliff (Ross Ice Front) rising about 30 m above the water. The other boundaries are bordered by glaciers and mountains, the glaciers supplying much of the deeper ice of which the ice shelf is composed. It has been shown by Crary and others (1962) that surface temperature, accumulation, and snow density all display non-uniform characteristics in the interior of the ice shelf. This is thought to be due to the apparent interactions between coastal circuiting low-pressure systems and the inland high-pressure pattern (Vickers, 1966). The orographic effects of the Transantarctic Mountains and the katabatic flow on to the ice shelf from both West and East Antarctica will also affect the movements of weather systems (see Warburton and Linkletter, 1978).

The distributions of total cloudiness (van Loon, 1972), cyclonic centers, and cyclonic frequency maxima (Taljaard, 1972) during all seasons show that most maritime storms affecting the Ross Ice Shelf originate over water in the high latitudes and pass near the southwest corner of the Ross Ice Shelf in the vicinity of Roosevelt Island. Some of these storms continue their movement into West Antarctica, eventually curving back across mid-continent. Many of the storms coming from the ocean move along the western boundary of the ice shelf, either to penetrate the Transantarctic Mountains to the interior of the continent or, under the influence of blocking high-pressure systems over the Polar Plateau, to be confined to the lower elevations of West Antarctica including the Ross Ice Shelf. Synoptic meteorology studies have shown that few of the cyclonic systems crossing the Antarctic coast come from lower latitudes.

#### CHEMICAL DEPOSITION ON ROSS ICE SHELF

Earlier work by Murozumi and others (1969) has shown, from work in West Antarctica, that the marine aerosol is probably the dominant source of impurities in Antarctic snow and ice. In particular, for the Ross Ice Shelf, Herron and Langway (1979) have demonstrated that the predominant source for sodium is sea salt and that aluminum concentrations are comparable with those at interior sites on the continent and is thereby probably of continental dust origin. They concluded that sodium maxima, which they found in vertical chemical profiles at three sites on the Ross Ice Shelf, are seasonal in nature, occurring in the winter or early spring as was the case for Greenland ice. Warburton and others (1981) have suggested that the ocean is the principal source of silver in snow on the Ross Ice Shelf; manganese and iron, on the other hand, manifest crustal ratios on the ice shelf. Warburton and Linkletter (1977, 1978) have further suggested that on the Ross Ice Shelf the locations of chemical features of depth profiles in the snow at different sites are related to the corresponding accumulation at those sites.

#### FIELD PROGRAM AND ANALYSIS PROCEDURES

During the 1974-75 and 1976-77 austral summers the snow-pack on the Ross Ice Shelf was intensively sampled in 2 m deep pits at seven sites (Fig. 1). The sites, RISP-BC base camp (RISP-BC), C7, and Roosevelt Island camp (RIC) were sampled during the 1974-75 field season. J9, F9, Roosevelt Island (RI), and Q13 were visited during the 1976-77 field season. The hygienic sampling procedures and laboratory analysis techniques have been described by Warburton and others (1981).

A total of 360 snow samples was collected from these sites. They were returned to the laboratory and kept frozen until analyzed. For analysis, the samples were melted in their original containers and analyzed by atomic absorption techniques for Na, Mg, Ca, and K. The detection limits for each element were  $4 \times 10^{-4}$   $\mu\text{g/l}$  for Na and Mg,  $8 \times 10^{-3}$   $\mu\text{g/l}$  for K, and  $5 \times 10^{-2}$   $\mu\text{g/l}$  for Ca. The analytical procedures gave standard deviations in the range of 5-15%.

## RESULTS AND DISCUSSION

*Temporal changes in chemical concentrations*

Figures 2 and 3 show the concentrations of Na, Mg, Ca, and K with depth at the seven sampling sites. There are distinct maxima and minima occurring for all four elements at each site. The maxima and minima were not associated with any particular feature of the stratigraphy such as wind crust, depth hoar, or firn, nor with any particular depth within a specific layer. Instead, they occurred in all of the different stratigraphic features and at many different depths within those features. This result agrees with the observations of Langway and others (1977) in Greenland ice. In any one profile the variations in the concentrations of the four elements are generally well correlated. The average correlation coefficients amongst the

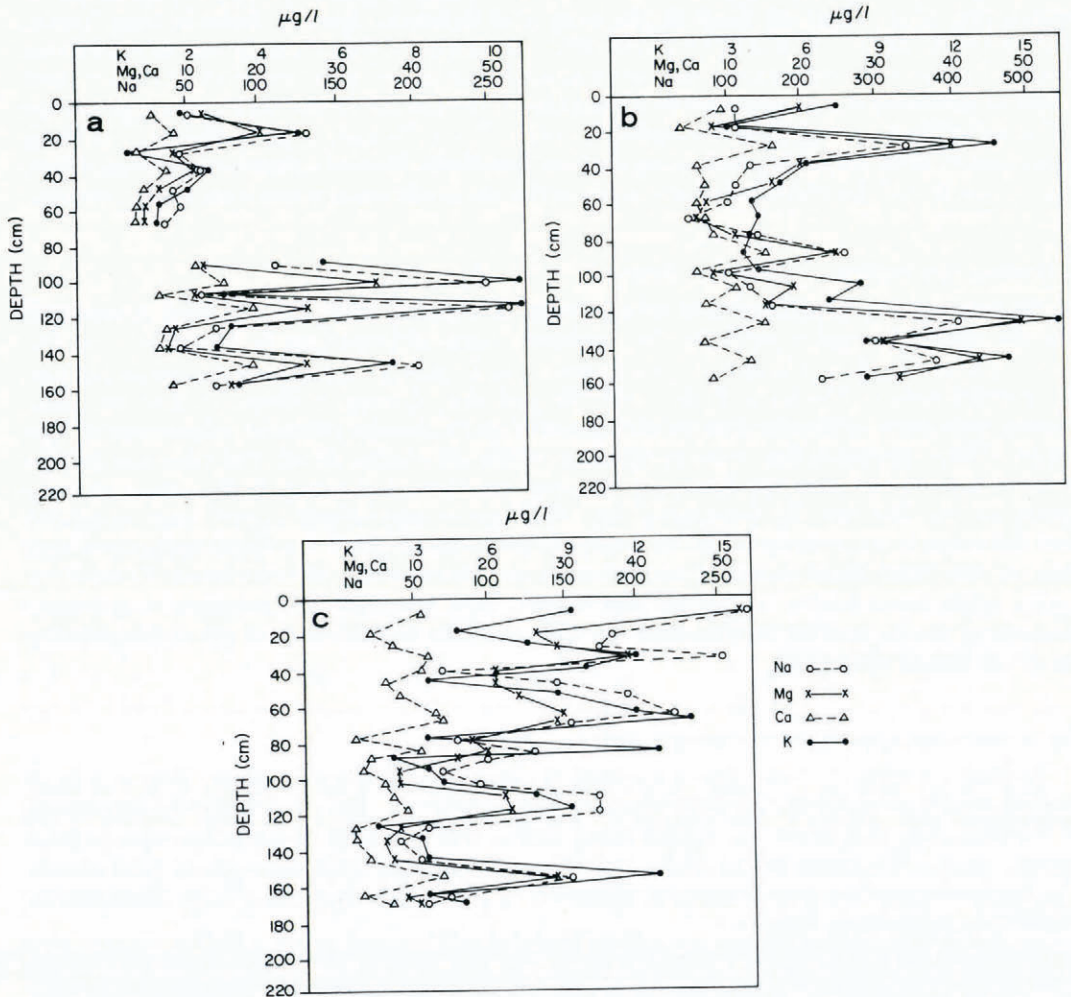


Fig. 2

- a. Temporal variations in concentrations of Na, Mg, Ca, and K at site RISP-BC.  
 b. Temporal variations in concentrations of Na, Mg, Ca, and K at site C7.  
 c. Temporal variations in concentrations of Na, Mg, Ca, and K at site RIC.



elements at all sites were 0.96 for Na : Mg, 0.80 for Ca : Na, and 0.74 for K : Na. The Fg site has some low correlation coefficients for K : Na and Ca : Na, even though the order-of-magnitude variations are still evident.

### Chemical profile cycles

In the absence of independent dating information (e.g.  $\beta$ -activity), it is difficult to identify a specific chemical maximum, in real time, in a particular profile. The cyclic nature allows only for the estimation of accumulation from peak to peak. Once a specific feature is identified by year of occurrence, the remaining cycles are then able to be dated. This factor explains the change in choice of the most recent maximum for the RIC profile from that chosen earlier by Warburton and Linkletter (1978). Although this indicates an undesirable degree of

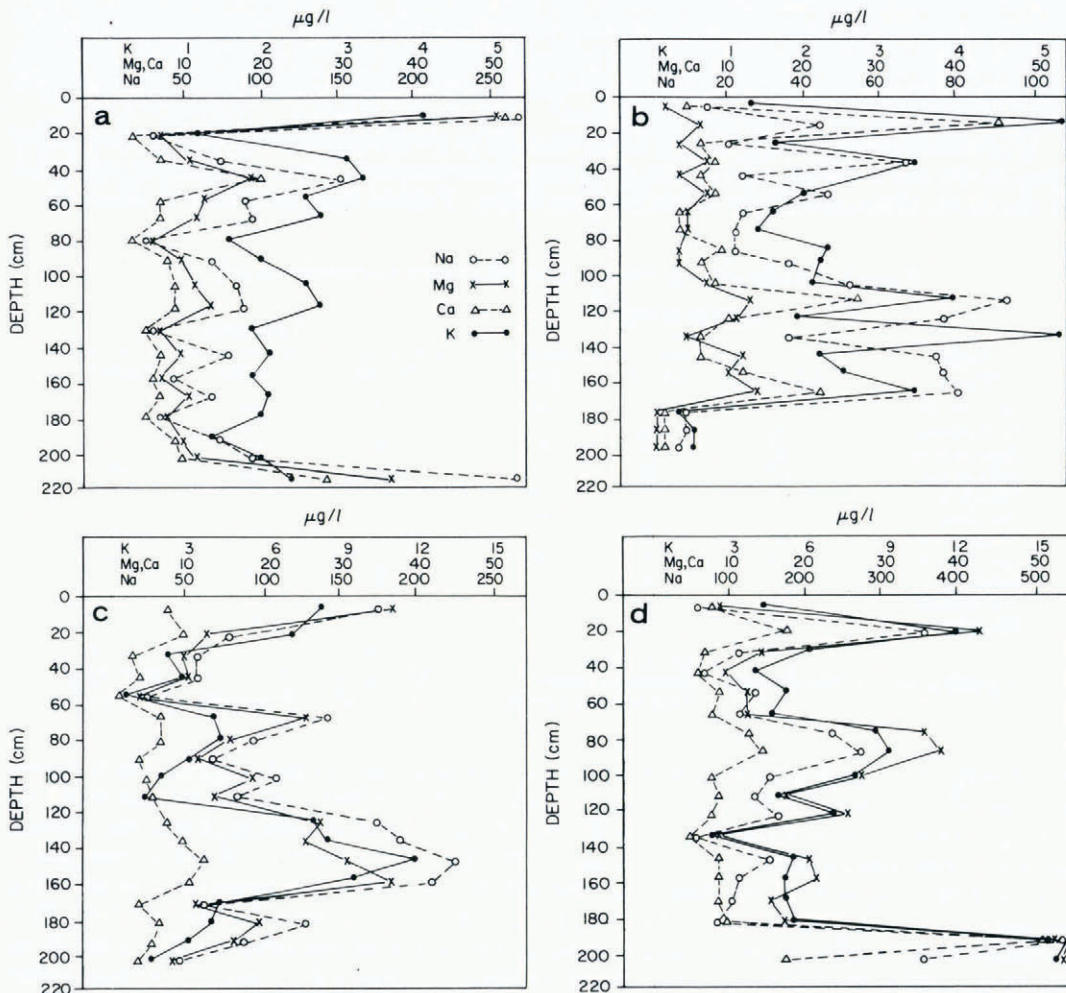


Fig. 3

- Temporal variations in concentrations of Na, Mg, Ca, and K at site J9.
- Temporal variations in concentrations of Na, Mg, Ca, and K at site F9.
- Temporal variations in concentrations of Na, Mg, Ca, and K at Roosevelt Island site.
- Temporal variations in concentrations of Na, Mg, Ca, and K at site Q13.

subjectivity, it has little, if any, effect on the use of this chemical method for estimating ratios of accumulation between sites, given a set of cycles for each site.

The data presented in Figures 2 and 3 show a sampling frequency of three to four data points per ion concentration cycle. At sites J9 and F9 the same profiles were sampled at a frequency of 20 data points per cycle with no change in the number of cycles observed. This result, reported elsewhere by Warburton and others (1981), suggests that a 10 cm deep sample is close to the minimum needed for such chemical definition on the Ross Ice Shelf.

#### Site-to-site correlations

When comparing chemical profiles at different locations on the Ross Ice Shelf, it should be noted that two separate field seasons were involved in the sampling. Sites C7, RISP-BC, and RIC were sampled in 1974–75 and J9, F9, RI, and Q13 were sampled in 1976–77. Several independent studies by Crary and others (1962), Clausen and Dansgaard (1977), and the present authors have made estimates of accumulation at one or more of these sites and, although these estimates are generally different for any one site, the ratios of accumulation between sites tend to be relatively consistent.

Warburton and Linkletter (1977) have reported on good correlations found in the profiles taken at C7 and RISP-BC sites during the 1974–75 field season. These correlations depended on the ratios of accumulations determined by Crary. Table I is an extension of this work.

TABLE I. CORRELATION OF PROFILE FEATURES AT SITES SAMPLED IN 1974–75

Profile feature	Depth below surface cm			Depth ratios		
	RISP-BC site	RIC site	C7 site	RIC/BC	C7/BC	C7/RIC
Maximum	18	15	25	0.8	1.4	1.7
Minimum	30	25	—	0.9	—	—
Maximum	38	37	—	1.0	—	—
Minimum	48	43	70	0.9	1.5	1.6
Maximum	—	65	90	—	—	1.4
Minimum	—	78	100	—	—	1.3
Maximum	100	90	130	0.9	1.3	1.4
Minimum	105	98	140	0.9	1.3	1.4
Maximum	115	115	150	1.0	1.3	1.3
Minimum	135	135	—	1.0	—	—
Maximum	145	155	—	1.1	—	—
Correlations of profile features		Correlation coefficient		$\gamma = 0.99$	$\gamma = 0.99$	$\gamma = 0.99$
		Regression slope		$M = 1.05$	$M = 1.27$	$M = 1.27$
		Regression intercept		$B = 6.48$	$B = 4.83$	$B = 9.02$

Blanks in the tables represent depths where no samples were taken, which usually occurred at sites of hard crusts. The maxima and minima in the profiles at RISP-BC and RIC are highly correlated, with a correlation coefficient of 0.99. Using Crary's isopleths, the average accumulation rate at RISP-BC is approximately  $145 \text{ kg m}^{-2} \text{ year}^{-1}$ , and the accumulation rate at RIC is expected to be close to  $150 \text{ kg m}^{-2} \text{ year}^{-1}$ . The mean depth ratio, represented by the regression slope  $M$  in Table I is 1.05 for the chemical features in the two profiles. This supports Crary's relative accumulation rates at the two sites and suggests that there is an identical origin (probably the same meteorological or seasonal events), producing these relatable precipitation chemical features.

Crary's accumulation rate at C7 is  $187 \text{ kg m}^{-2} \text{ year}^{-1}$ . With similar snow densities at the three sites, this gives an accumulation ratio between C7 and RISP-BC or RIC of a little less than 1.3. The mean depth ratios in Table I between C7 and the other two sites (RISP-BC and RIC) are both 1.27 with 0.99 correlation coefficients, demonstrating close relationships



amongst the profile features at the three sites separated by distances up to 440 km. The slopes of the regression lines (1.27) represent the ratios of accumulations between C7 and the other two sites.

More extensive sampling was done during the 1976-77 field season, particularly at sites J9 and F9. Three pits were dug at each of these sites and sampled in an identical manner. Two profiles were taken from each pit about 3 m apart horizontally. A third profile was also taken at each site from separate pits located approximately 3-4 km from those yielding the other two profiles. Table II lists the depths of the chemical-profile features at J9 and F9. The depths of the maxima and minima in chemical concentrations of Na, Mg, Ca, and K are best estimates for those layers using all three profiles available at each site and the stratigraphy of the pits. The results show that the chemical features are highly correlated ( $\gamma = 0.99$ ) at these two sites. The regression slope ( $M = 1.17$ ) represents the best-fit depth ratio for the features and therefore would represent the ratio of accumulations at the two sites.

TABLE II. CORRELATION OF CHEMICAL PROFILE FEATURES AT SITES J9 AND F9, ROSS ICE SHELF

Profile feature	Depth below surface cm		Depth ratios J9/F9
	J9 site	F9 site	
Maximum	10	—	—
Minimum	25	22	1.1
Maximum	50	38	1.3
Minimum	80	75	1.1
Maximum	95	90	1.1
Minimum	110	105	1.1
Maximum	130	115	1.1
Minimum	165	135	1.2
Maximum	185	150	1.2
Minimum	195	170	1.1
Maximum	215	190	1.1
Correlations of profile features	Correlation coefficient		$\gamma = 0.99$
	Regression slope		$M = 1.17$
	Regression intercept		$B = -2.12$

#### Total $\beta$ -activity measurements at J9 and F9 sites

The measurements of total  $\beta$ -activity and snow densities in two separate 5 m deep pits at J9 and F9 sites on the ice shelf provided an independent means of estimating the mean annual accumulation at these sites. Figures 4 and 5 give the total  $\beta$ -activity as functions of snow depth, and from these results the mean accumulations at these two sites have been estimated as 94 kg m<sup>-2</sup> year<sup>-1</sup> at J9 and 84 kg m<sup>-2</sup> year<sup>-1</sup> at F9, for the 12-year period 1965-76 (see Table III). Therefore, the ratio of  $\beta$ -activity determined accumulations at the two sites is 1.12. This is in modestly good agreement with Clausen and Dansgaard (1977) who, for these same two sites (J9 and F9), estimated the accumulations at 90 and 76 kg m<sup>-2</sup> year<sup>-1</sup>, respectively, and a ratio of 1.18 for the period 1955-74. Hence, there is good agreement between accumulation ratios determined by total  $\beta$ -activity measurements and that determined from chemical profiles at these two sites.

#### Meteorological and seasonal variations

Further inspection of Figures 4 and 5 shows that the 220 and 190 cm snow depths at J9 and F9 correspond approximately to 1968 or 1969 at the two sites. Since these are the approximate depths to which pits were sampled at J9 and F9 for the chemical analyses in the 1976-77 austral summer, it would appear that the chemical profiles in Figure 3a and b

represent 7 to 8 years of accumulation, and it can be conjectured that the oscillations in chemical concentrations are annual-seasonal. However, no temperature-related characteristics (e.g.  $\delta^{18}\text{O}$  values) are available to determine whether this is so.

Langway and others (1977) have described the seasonal variations of chemical constituents in annual layers of Greenland ice deposits. They found that the maxima in Na, Mg, Ca, K, and Al occurred in the early spring, and the minima in the later summer and early autumn. The ratios of maximum to minimum concentrations for Na and Mg were an order of magnitude and the present results for the Ross Ice Shelf also show such ratios. Herron and Langway

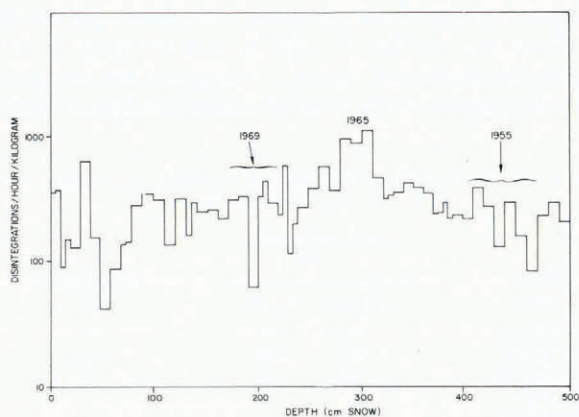


Fig. 4. Total  $\beta$ -activity at site J9, as a function of depth of snow, indicating possible  $\beta$ -activity horizons.

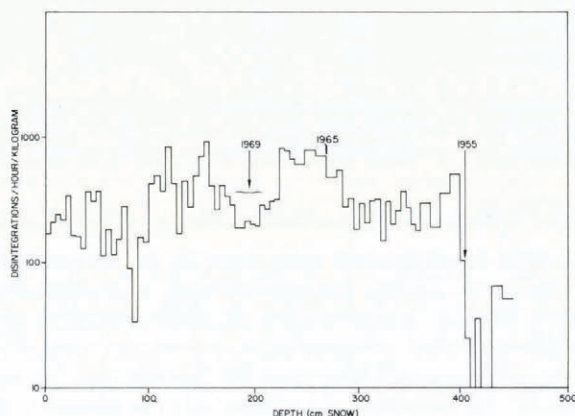


Fig. 5. Total  $\beta$ -activity at site F9, as a function of depth of snow, indicating possible  $\beta$ -activity horizons.

TABLE III. ACCUMULATION AT SITES F9 AND J9 ON ROSS ICE SHELF BASED ON  $\beta$ -ACTIVITY HORIZONS AND MEAN SNOW DENSITY

Site and sampling date	Snow depth for January 1965 m	Mean density $\text{Mg m}^{-3}$	Mean accumulation $\text{kg m}^{-2} \text{ year}^{-1}$
F9 (January 1977)	2.70	0.375	84
J9 (January 1977)	3.00	0.378	94



(1979) have suggested that the sodium maxima which they observed in snow and ice cores at three sites on the Ross Ice Shelf, occurred in the winter and early spring. It is therefore of interest to discuss when the maxima and minima might have occurred at the several Ross Ice Shelf sites and also how this relates to accumulation.

Earlier work at Roi Baudoin Station (Bentley and others, 1964), near the coastline of north-east Antarctica, showed from  $^{18}\text{O}/^{16}\text{O}$  measurements that the average depths of accumulation during the cold and warm parts of the year were about the same. Goldthwait (1958) found a maximum in accumulation in the late autumn (May–June) at Byrd Station. One of the more extensive detailed investigations of annual and seasonal variations of snow accumulation in West Antarctica was carried out by Vickers (1966), who showed for Little America V and Byrd Station that autumn and spring were the two seasons with highest accumulation. It was also shown that the effects of well-defined weather systems are often widespread areally, and that the meteorological record directly correlates with known stratigraphy over large areas of West Antarctica including the region of the Ross Ice Shelf covered by this present study. Using weather maps and snow-stake farms, Vickers found that most of the large storms affect wide areas of western Antarctica almost simultaneously ( $\pm 2$  d), and that it was possible to trace a given meteorological phenomenon laterally in the stratigraphy over horizontal distances in excess of 1 000 km.

Autumn and spring in Antarctica are characterized by alternating build-up (autumn) and decline (spring) of the inland high-pressure systems. At maximum areal extent (winter), the high is able to check the poleward migration of maritime lows near the coast. However, these maritime lows do make inroads in the autumn and are coincident with times of maximum precipitation. Snow accumulation at this time of the year along the Ross Ice Front can be greatly affected by strong onshore winds from the easterly quadrant of an intensified Ross Sea low-pressure system. It is also common for successive maritime lows along the Wilkes Land coast to cross Cape Adare and strongly reinforce a persistent low in the Ross Sea. The result is often intense and prolonged autumn storms.

When these occur, a greater proportion of the sea surface is occupied by breaking waves, leading to a higher production rate of sea-salt nuclei (Toba, 1961) and a greater mass transfer of this material into the near-surface boundary layer. The larger wave action at the sea surface will also mix any chemically enriched surface layers with deeper water. Thus marine aerosols generated during these storms would be expected to contain chemical constituents, the concentration ratios of which would be similar to those in bulk sea-water. The larger amounts of precipitation which occur should contain, therefore, an abundance of marine trace metals accompanied by the less abundant components of the global background aerosol which is probably always present. The overall concentrations of most elements in the precipitation should be higher due to the higher chemical loading of the lower atmosphere under these high shearing-stress conditions. Not only would this explain the peaks in concentrations in the chemical profiles of the snow-pack but also the good correlations between the elements in any one profile.

Since these autumn storms occur when the sea-ice extent is near its minimum (Gordon and Taylor, 1975), and the open sea surface (the source of marine aerosols) is closer to the ice front than in winter and spring, it is considered that this last factor, combined with the higher frequency and intensity of storms in autumn producing precipitation over the western part of the Ross Ice Shelf, leads to the production of chemical concentration maxima in the snow-pack profiles. However, significant springtime accumulation has also been documented and this must also be considered in terms of chemical fluctuations in the snow-pack.

When the shearing-stress conditions in the boundary layer are lower, the atmosphere is more stable with light winds and less precipitation. This is more frequently the case in summer on the Ross Ice Shelf. Under these conditions, the total particulate loading in the lower atmosphere is less, due to a lower contribution from the oceanic-origin aerosols. The global



background aerosol represents thereby a proportionately greater component of the impurities in the atmosphere and this should be reflected in the chemical composition of any precipitation falling during these periods. The overall effect on the precipitation chemistry would be to produce elemental ratios different from those in bulk sea-water and to give lower concentrations.

## CONCLUSIONS

Marked changes in concentrations of the elements Na, Mg, Ca, and K have been observed as a function of depth in seven 2 m deep pits sampled on the Ross Ice Shelf. 2 m of snow accumulation at these sites represents time periods ranging from 5 to 8 years. The concentration changes (maxima to minima) cover a range of up to 10 : 1 for all four elements. Since the changes in concentration as a function of depth for all four elements at any one site are highly correlated, it is concluded that the impurities probably come from the same sources.

Strong temporal relationships exist amongst the chemical variations at the several sites sampled on the ice shelf. First, the profile characteristics at sites J9 and F9 are highly correlated. These two sites are approximately 220 km apart. It is concluded that these two sites experience, in general, the same meteorological phenomena at the same time. The depth ratio of the several chemical features at the two sites is 1.17, in good agreement with the accumulation ratio determined by total  $\beta$ -activity measurements, showing that the chemical characteristics can be used for determining, at least, relative accumulations. Sites C7, RISP-BC, and RIC also show good correlations amongst the profile features. The depth ratios of corresponding chemical features are in good agreement with the ratios of average accumulation for these sites determined by Crary and others (1962). These three sites are up to 440 km apart.

It is suggested that the chemical variations with depth are caused by meteorological and probably seasonal factors. On some occasions these factors are favorable to the accumulation of snow with higher chemical concentrations having a predominantly marine origin. The most favored season appears to be autumn, when more frequent heavy snow-fall storms occur on the Ross Ice Shelf, and when sea-ice extent is near its minimum. However, significant snow accumulation has also been documented in the springtime season and this cannot be ruled out as an important period relating to chemical features, for at least some years. On other occasions, the meteorological and seasonal factors are favorable to the production of lower overall concentrations of the cations measured (Na, Mg, Ca, and K).

It is hypothesized that the chemical concentrations are functions of the shearing stress in the lower boundary layer. High shearing-stress conditions with associated strong winds, rougher sea surfaces and greater vertical mixing in the lower layers of the atmosphere, particularly in the autumn months, would lead to coincident chemical characteristics in the snow-pack at widely separated sites, and chemical composition indicative of predominantly marine sources. This season would also correspond to the period near sea-ice minimum, bringing the marine aerosol source closer to the permanent ice-shelf front which would lead to correspondingly higher marine-origin impurities at any site compared with the same site at times of the year when the sea ice may extend for hundreds of kilometers beyond the ice shelf. Low shearing-stress conditions, on the other hand, would be conducive to lower mass transfer to the near-surface boundary layer from the sea, with resulting lower concentrations in the snow at all sites on the Ross Ice Shelf.

The high correlations between chemical features in the snow-pack at different sites provide a basis for determining relative accumulation values for these sites. If these relative values can be combined with independently determined "absolute" values at a reasonable number of sites on the ice shelf, chemical characteristics can be used to develop total snow-pack accumulation data not only for the Ross Ice Shelf but for other large regions of the Antarctic continent.



## ACKNOWLEDGEMENTS

We wish to thank J. V. Molenaar, M. S. Owens, A. V. Anderson, and D. LaMontagne for their assistance in the field programs and laboratory analysis work. We also wish to thank C. Cornish for measurements of  $\beta$ -activities and Dr C. Lorius and the Laboratoire de Glaciologie staff for their support. This work was supported by the Division of Polar Programs of the National Science Foundation under Grant Nos OPP73-05842-A01 and DPP77-22817.

MS. received 24 April 1980 and in revised form 20 October 1980

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