# The transport of moisture into the antarctic interior

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(Manuscript received June 25, 1968)

ABSTRACT

The magnitude of the moisture transport by the atmosphere into the Antarctic interior is determined from a mass transport model which allows a longitudinal variation in the annual flux values. It is indicated that the use of monthly mean transport and temperature values underestimates the annual moisture transport required by observed accumulation values in the interior, consequently a relatively much larger fraction of the annual moisture transport must occur in conjunction with positive temperature deviations from mean monthly values. This relation is examined at Byrd station where it was found that during the austral summer 1957–8 the threeday period with the highest 700 mb temperature accounted for nearly 20 % of the annual moisture transport. The variation of the moisture transport with altitude is examined and its effect as a constraint upon the maximum central height that the ice sheet may attain is briefly discussed.

## Introduction

One of the more important, but heretofore generally neglected aspects of Antarctic meteorology is the mechanism by which the large amounts of precipitable water required to nourish the inland ice sheet are transported into the continent. Since the annual increments of the net snow accumulation are fairly easily identified by stratigraphic methods (e.g. Gow, 1965), estimates of the annual ice mass budget are generally made without reference to meteorological or climatological conditions, although their inclusion would very likely give a better definition of the dynamic situation which is interacting with the underlying surface.

The problem that will be considered here is simply to determine how and where the mass of water enters the Antarctic continent and is carried into the interior. This will involve analysis of the mass flow over the continent and consideration of the probable moisture content of the air. Some implications of the results will also be discussed, particularly with reference to the problem of whether the total ice mass is presently increasing or decreasing.

The flow of air over the Antarctic continent also is an important parameter in the study of a number of related questions concerning the heat balance of the continent and the role that the continent plays in affecting the climate at lower latitudes.

Since the routine measurement of atmospheric moisture content at very low temperature is both difficult and imprecise, the direct evaluation of the total moisture transport will not be attempted, except for a short analysis of the actual temperature-moisture covariance at one station, but rather the feasibility of moisture transport will be considered in combination with various Antarctic circulation models. Such a general treatment of course only yields limiting conditions and possible mechanisms, but does provide an insight into the ice mass balance of the Antarctic interior.

## The two-layer circulation model

The most recent treatment of the mass budget of the Antarctic atmosphere is that of Rubin & Weyant (1963), which presents a consistent pattern of outflow in the lower troposphere and inflow in the upper troposphere and stratosphere, involving a balanced flux of $65 \times 10^{12}$ gm/sec. This conceptually simple model of upper level inflow, sinking motion, and low level outflow is similar to one proposed for Greenland by Hobbs (1945), and is in agreement with that postulated for the Antarctic from ozone transport values (Wexler *et al.*, 1960). Furthermore it provides an adiabatic heat source to offset the large continental radiative losses. However such a model cannot be reconciled with the transport of water vapor since on the average it suppresses precipitation, and assigns the mass influx to such a high altitude that little moisture can be transported into the interior. Apparently the peripherally averaged situation is never actually realized, and the mathematically determined mean state may not be equated to a physical equilibrium or steady state.

The Rubin-Weyant model utilizes a circular equivalent continent with a radius of 2000 km, and was developed from coastal station data. It therefore includes an edge effect which places the boundary between inflow and outflow at a much lower altitude than can be expected in the interior. As one goes inland from the coast, the zero net transport level should rise approximately as the ice surface, and the already difficult moisture transport process will be confined to more hostile altitudes.

An alternate hypothesis, which seems more reasonable from a synoptic point of view is that large deviations of the meridional wind components from their average values exist in space or time. Either supposition however, produces a mass transport pattern that is unlike the mean peripheral pattern.

The tabulated values of the circumferential monthly mean meridional winds given by Rubin & Weyant allow a determination of the temporal variability, although not of the spatial variability of the mean mass flux. These show that there was, on the average, outflow at and below 700 mb and inflow at and above 500 mb around the periphery of the Antarctic continent in every month included in the study. It follows therefore that longitudinal variations in the mass flux must exist, and that there must be preferred sectors of inflow and outflow on the Antarctic continent.

A consideration of the water vapor transport required to produce the observed snow accumulation in the interior leads to the conclusion that the preferred sectors of inflow must necessarily transport relatively large amounts of water vapor and that the inflowing air must therefore be relatively warm. This of course is also required from considerations of the total atmospheric heat budget. If it is assumed that the mean annual precipitation amount over the Antarctic interior is roughly 10 cm of water, then a flux of $0.04 \times 10^{12}$ gm/sec of water vapor into the equivalent continent is required. In conjunction with the previously given value of the mass flux, this loss implies a decrease in mixing ratio of 0.62 gm/kg for the inflowing air during its residence time over the continent, which is an appreciable change in the Antarctic. Mean conditions at Amundsen-Scott station for example produce a saturation mixing ratio at the surface of only about 0.66 gm/kg, thus stated very simply, air flowing into the interior must be saturated, while air flowing out of the interior must be dry, a condition that is difficult to achieve in practice.

## Peripheral variation of the mass flux

The peripheral variation of the mean annual mass flux was computed for Rubin and Weyant's equivalent circular continent, using actual radial wind components rather than meridional wind components, although this refinement is only of moderate importance since the greatest angular difference between the radial and meridional direction does not exceed 23°. The analysis was carried out from the surface to 50 mb in three increments: Sfc to 600 mb, 600 to 350 mb, and 350 to 50 mb.

The mean annual, vertically integrated mass flux values for the peripheral stations are given in Table 1. Since the stations are not spaced equally on the perimeter of the equivalent continent, mass flux values are presented for a unit area defined as a one centimeter wide strip extending from the top to the bottom of each layer. Mass outflow has been defined as positive. The distribution of the annual net mass flux is also shown in Fig. 1 with the stations identified by their number in Table 1.

Examination of Table 1 shows that preferred sectors of inflow and outflow definitely exist. On the average the mass flux is positive in Wilkes Land and in the Weddell Sea region, and negative in the eastern Ross Sea, Marie Byrd Land and much of East Antarctica. Maximum values of mass inflow occur at Byrd and Mirny, while maximum values of mass outflow occur at Hallett and Dumont d'Urville. The outflow at Hallett could be due to the large angle between the boundary of the equivalent

Table 1. *Distribution of the net annual mass flux around the periphery of the Antarctic continent*

| | | Mass flux intensity ($10^4$ gm/cm/sec) | | |
|---|---|---|---|---|
| Index | Station | Sfc–600 mb | 600–350 mb | 350–50 mb |
| 1 | Norway Base | 4.0 | 2.7 | −4.8 |
| 2 | Halley Bay | −0.4 | 2.3 | 3.8 |
| 3 | Ellsworth | 2.5 | 2.0 | 4.7 |
| 4 | Byrd | −11.2 | −8.4 | 2.0 |
| 5 | Little America V | −0.5 | −3.0 | 7.1 |
| 6 | Hallett | 10.7 | 5.6 | 15.1 |
| 7 | Dumont d'Urville | 5.2 | 4.4 | 5.2 |
| 8 | Wilkes | −4.1 | −0.1 | −2.6 |
| 9 | Mirny | −1.6 | −1.4 | −5.0 |
| 10 | Davis | −6.0 | −4.0 | −3.1 |
| 11 | Mawson | 4.0 | 3.7 | −4.7 |
| 12 | Molodezhnaya | −0.3 | 3.1 | −6.3 |
| 13 | Roi Baudouin | 2.8 | −2.9 | −5.6 |
| 14 | Lazarev | 6.9 | −0.2 | −6.0 |
| Integrated mass exchange | | $31.7 \times 10^{12}$<br>−32.2 | $20.3 \times 10^{12}$<br>−20.2 | $33.4 \times 10^{12}$ gm/sec<br>−33.2 |
| Total exchange $85.4 \times 10^{12}$ gm/sec | | | | |

*Data sources:* Stations 1–9, 14, U.S. Navy Marine Climatic Atlas of the World, Vol. VII, Antarctic, NAVWEPS 50-1C-50, Sept. 1965. Stations 10–13, U.S. Dept. of Commerce Weather Bureau, Monthly Climatic Data for the World.

continent and latitude lines, so that circumpolar flow would appear to have a radial component, however since there is no corresponding inflow at Ellsworth, this effect seems to be a minor one.

This distribution of inflow and outflow may be modelled schematically by an elongated region of low pressure centered approximately on the south pole, with one trough extending roughly along the zero meridian and the other along

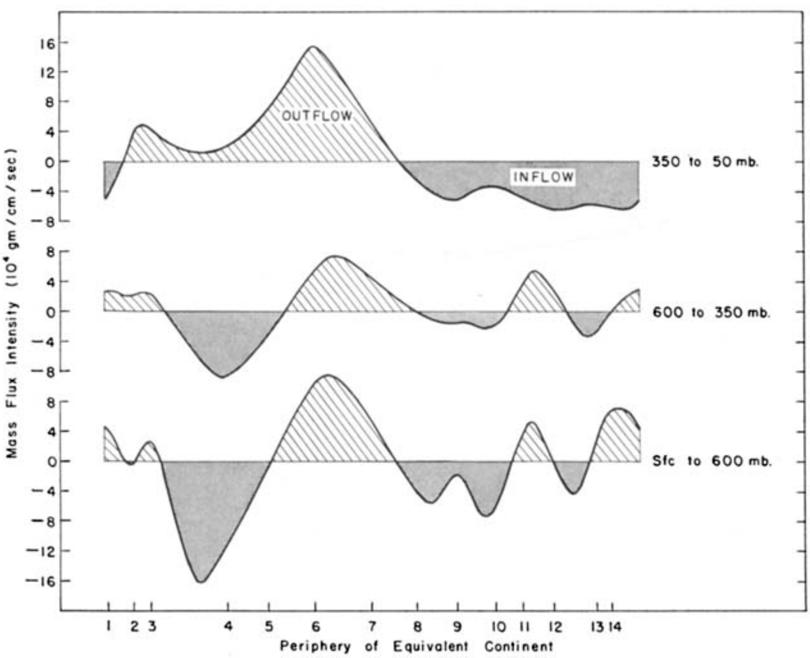


*Fig. 1.* Peripheral distribution of the annual net mass flux for the equivalent continent.

160° E longitude, which coincides in fact with one of the two basic types of atmospheric circulation found in the Antarctic by Astapenko (1964).

The empirically determined total mass exchange of the Antarctic atmosphere (cf. Table 1), is $85.4 \times 10^{12}$ gm/sec, which is roughly 30% higher than the value $65 \times 10^{12}$ gm/sec obtained from the Rubin–Weyant circulation model. That the two values are unequal is not surprising, and in fact the higher value found here is more desirable from the standpoint of moisture exchange.

A seasonal variation of the basic pattern is evident at some stations. For example at Byrd, Dumont d'Urville and Wilkes, the mass flux changes sign during the year, being negative (inflow) in summer and positive (outflow) in winter. At Little America V there is less inflow in winter than in summer, and at Hallett there is less outflow in winter than in summer, indicating a seasonal variation in the Ross Sea circulation. At Mirny there is a semi-annual variation with inflow in summer and winter, but zero flux at the time of the equinoxes. These variations are of course only reflections of the seasonal shifts of the mean pressure distribution around the Antarctic perimeter, but for the purpose of this paper, it should be noted that the austral summer, which is the period during which the upper limit of the moisture transport is high, is also one of wide-spread low-level inflow into the continent, with outflow being confined to the Hallett and Ellsworth sectors.

## Mass flux in the interior

In order to determine whether or not the observed mass flux values represent only a coastal phenomenon, a second arbitrary volume was constructed, extending from the surface to 100 mb, and roughly encompassing Amundsen–Scott, Vostok II, and Plateau stations. The circular base has a radius of about 720 km, and is centered at 83.5° S, 66° E. Plateau station has only been used as a residual to balance the mass flux at Vostok II and Amundsen–Scott, since data for it is not now available. The mass flux values for these stations show that generally the peripheral conditions extend substantially inland. Thus the inflow at Amundsen–Scott and Plateau is a continuation of the mass inflow at Byrd and Roi Baudouin, while the outflow at Vostok II is a source for the mass flux at Hallett and Dumont d'Urville. The magnitude of the mass exchange is $22.1 \times 10^{12}$ gm/sec, which is an appreciable fraction (26%) of the total mass flux through the equivalent continent, in spite of the fact that the inner volume is little more than one tenth that of the equivalent continent. Such a rapid exchange of air is of course very favorable for the deposition of sizeable amounts of moisture at very low temperatures.

Loewe (1962) determined that the total water vapor content over the higher parts of the Antarctic ice cap would have to be replaced at least every fifth day in order to provide an accumulation of 7 to 8 cm per year. The above calculations indicate that this requirement is fulfilled since the representative residence time of a parcel of air in the inner volume, determined by taking the ratio of the mass within the volume to the exchange rate, is only about 5.7 days.

## The transport of moisture

The largest fraction of the lower level annual mass influx occurs in the Byrd–Amundsen–Scott sector, consequently it may be presumed that a similarly large fraction of the moisture transport is carried through this sector. Since the actual moisture transport is difficult to measure, monthly values of the saturation mixing ratio will be considered, with a weighting factor of 60% relative humidity applied for transport values. The assumption of such a value is quite good for Byrd throughout the year.

The average annual amount of precipitation observed on the Antarctic continent is of the order of 10 cm, requiring an annual water vapor flux of $1.26 \times 10^{18}$ gm into the interior. (A summary of flux values obtained by other investigators, which vary from 0.8 to $2.8 \times 10^{18}$ gm/year is given in Wexler (1961)). With the previously determined mass exchange value, this requires, on the average, a minimum mixing ratio of 0.47 gm/kg. In Fig. 2 a time section at Byrd is presented, which gives monthly mean saturation mixing ratio values converted from temperature data. Also indicated is the seasonal variation in the level of zero mass flux. It is evident, particularly in the austral summer, that the inflowing air is potentially quite moist although with an average relative humidity of

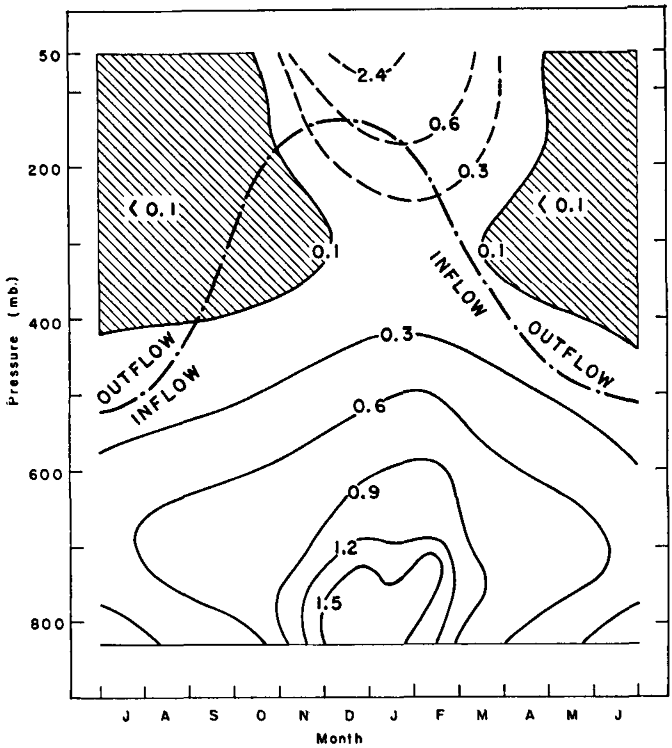


*Fig. 2.* Time vs. altitude section showing isopleths of saturation mixing ratio from monthly mean temperatures at Byrd. Also indicated is the boundary between net annual inflow and outflow.

60% the actual mean annual mixing ratio does not quite reach 0.3 gm/kg The high saturation mixing ratio values above 200 mb are solely a result of stratospheric, warming, and are not indicative of high moisture content. A computation of the total annual water vapor transport through the Byrd sector with these mean values yields a value of $0.30 \times 10^{18}$ gm water, which is roughly twentyfive percent of the total transport required for the entire continent, however since the annual mass flux through the Byrd sector amounts to forty percent of the total mass exchange, the water vapor transport falls short of the minimum required to explain the observed inland accumulation by a factor of about two.

There are two means of resolving this difficulty. One is that the inward moisture transport at Byrd is abnormally low relative to that at other peripheral stations, which does not seem very likely because of the lower coastal elevations in West Antarctica than in East Antarctica. The other is the assumption that the bulk of the moisture is carried by inflowing air warmer than the monthly mean temperatures, which seems reasonable because of the exponential variation of the saturation mixing ratio with temperature. This relationship will be investigated in a later section.

At Amundsen–Scott the transport of water vapor by the inflowing air, on an average basis, is nearly equal to the minimum required to explain the observed inland accumulation. The potentially greatest moisture carrying capacity of the air does occur near the surface where outflow from the interior is observed, however the mean saturation mixing ratio of the inflowing air above 550 mb reaches approximately 0.15 gm/kg (cf. Fig. 3). Although the actual mixing ratio of the inflowing air will therefore only be of the order of 0.10 gm/kg, such a low value is roughly sufficient to produce the quite small accumulation values of the Antarctic interior.

Assuming a mean annual deposition of 5 $gm/cm^2$ water equivalent over the inner area

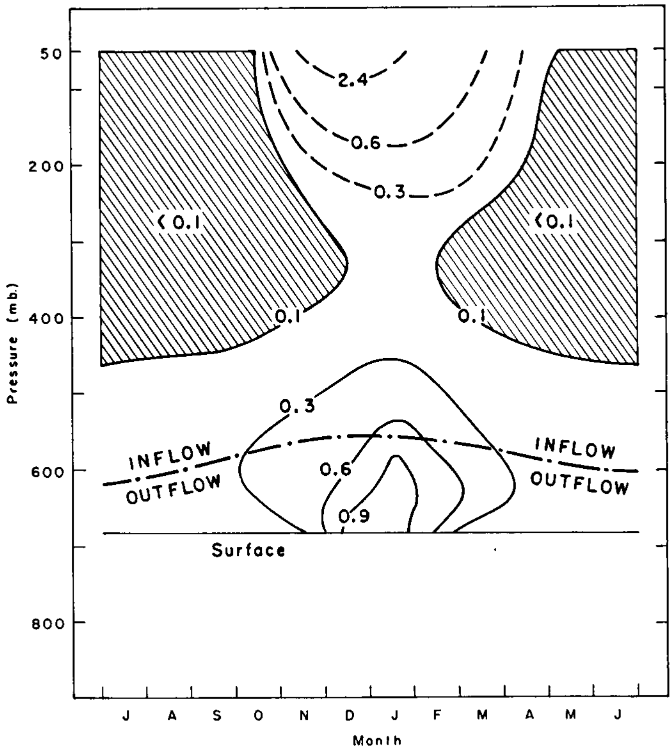


*Fig. 3.* Time vs. altitude section showing isopleths of saturation mixing ratio from monthly mean temperatures at Amundsen–Scott. Also indicated is the boundary between net annual inflow and outflow.

of radius 720 km, an annual water mass influx of $0.08 \times 10^{18}$ gm is required, which must enter through the Amundsen–Scott and Plateau sectors. The annual mass exchange through these sectors is $7.0 \times 10^{20}$ gm, thus the requisite mean mixing ratio need only be 0.11 gm/kg.

The situations at Byrd and Amundsen–Scott may be characterized as being respectively meteorologically and climatologically controlled. The influx of sufficient water vapor at Byrd is apparently dependent upon positive departures of the air temperature from its mean; thus if the short-term variability of the summer temperature (meteorological variation) were to decrease, the mass of water vapor transported into the interior through the Byrd sector would similarly decrease. At Amundsen–Scott such a mechanism is not required; a change in the variability of the air temperature about the monthly mean values would not affect the influx of sufficient water vapor to maintain the present mean accumulation rate. It would be affected only if the monthly mean temperatures themselves were to decrease.

## The temperature-moisture covariance at Byrd

The hypothesis that the bulk of the moisture is carried by the warmest air is consistent with the fact that the moisture transport calculated from average values is too low to explain the observed inland accumulation, and is strengthened by the exponential increase of the saturation mixing ratio with temperature at any given pressure level. The hypothesis may be tested by plotting the moisture flux against temperature. If the resulting cloud of points shows definite deviations from a straight line, then it may be assumed that the hypothesis is correct.

Such a computation was carried out for Byrd Station from October 1957 to April 1958. Fig. 4 shows individual daily moisture transport values as a function of temperature at 700 mb. The graph definitely shows that the moisture transport increases approximately exponentially with temperature, and that positive departures from the mean temperature (about −20°C) correspond to much greater positive

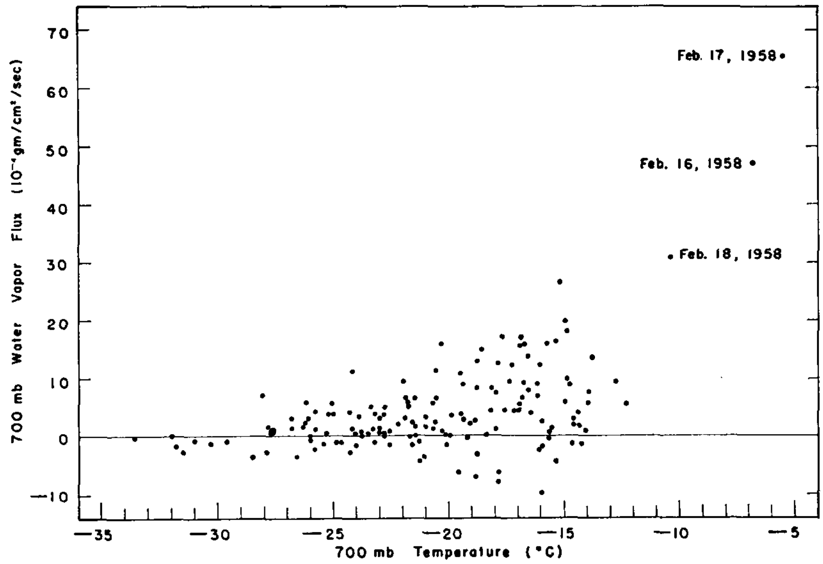


*Fig. 4.* Moisture flux as a function of the 700 mb temperature at Byrd station, October 1957–March 1958. Each dot represents a day on which data was available.

departures from the mean moisture transport value. At low temperatures (less than $-28°C$) the moisture transport is essentially independent of themperature and very close to zero. At more moderate temperatures (between $-28°C$ and $-20°C$) there is a definite tendency toward moisture transport into the interior and toward higher transport values. At temperatures above $-20°C$ the moisture transport increases rapidly and reaches values that are an order of magnitude greater than those observed at lower temperatures.

The total moisture transport for the summer season is given in Fig. 5 on a monthly basis together with the cumulative total through the summer. It is immediately evident that at least in 1957–58 the moisture transport did not follow a regular progression, but rather was quite variable throughout the season. While the October and April values are low, as would be expected from temperature observations, the January value is anomalously low, particularly when contrasted with the high February value.

The cumulative total transport reaches a value of $0.36 \times 10^{18}$ gm by the end of April, which, on the assumption that the five winter months contribute very little to the moisture flux into the interior, may be taken as nearly the annual value. While it exceeds that computed from the mean monthly data by twenty percent, it is less than that required to explain a mean precipitation value of 10 cm over the equivalent continent. (Since the mass flux at Byrd was 40% of the Antarctic total, the moisture flux should be 40% of $1.26 \times 10^{18} \approx 0.5 \times 10^{18}$ gm.) This of course is not a serious discrepancy because it is the result of a comparison between the observed transport in one year and an arbitrarily designated representative value, which may not reflect the actual precipitation value for any given year.

The meteorological control of the magnitude of the moisture transport at Byrd is very well shown by the February value, which is largely the result of one three-day period (February 16–18) during which a low pressure area was situated near Little America and warm moist maritime air was moving into the continent. The moisture transport during these three days, which are marked in Fig. 4, amounted to 40% of the monthly total, which itself amounted to nearly half the annual total. Therefore approximately one-fifth of the total annual moisture transport in the Byrd sector occurred during this particular three day period.

Since only one set of such high transport values was observed (cf. Fig. 4), it is apparent that this favorable synoptic situation appeared

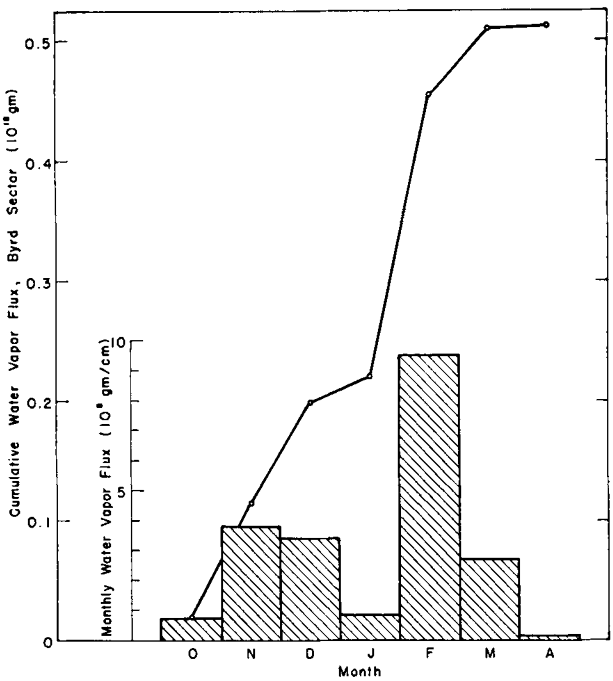


*Fig. 5.* Histogram of the monthly net moisture transport through the Byrd sector during the austral summer 1957–8. Also shown is the cumulative total moisture transport.

only once during the summer of 1957–58. There is however no reason to suppose that it cannot recur one or several times during one summer, but on the other hand, there is also no reason to assume that it need to occur at all. Then, because of the great influence of this situation on the total annual moisture transport, one would expect a high interannual variability in the moisture transport values. Furthermore it would follow that the observed annual accumulation amounts, which represent a rough measure of the annual moisture transport, should similarly be highly variable. This latter effect is indicated in a study by Giovinetto & Schwerdtfeger (1966), who found that the one-year lag correlation in the snow accumulation record over 200 years at the South Pole was very nearly zero, so that the annual succession of snow accumulation amounts is very nearly random. The accompanying standard deviation values indicate that individual annual values may vary from the mean by a factor of 2, producing a relatively large range of observed values, in accord with the moisture transport thypothesis at Byrd.

## Effect on ice mass balance

The mass balance of the interior ice sheet is a function of the ablative effects at its edge and its surface, and the accumulative effects of the precipitation pattern on its surface. Since neither its rate of gain nor its rate of loss can be calculated very precisely, the difference in the two rates, which determines whether the ice mass is increasing or decreasing is also not very well defined. It is however possible to place rough limits on the amount of ice that can be accumulated.

The detailed moisture transport values at various pressure levels at Byrd show that to a very good approximation these vary logarithmically with pressure, such that the transport is halved for a pressure decrease of 100 mb. This empirical observation is related to the fact that at Byrd a 100 mb pressure decrease corresponds to an increase in altitude of approximately 1500 m, through which distance the moist adiabatic lapse rate will produce a temperature decrease of approximately 10°C which in turn corresponds approximately to a decrease in the saturation mixing ratio of a factor of 2. On the further assumption of horizontal flow, and because of the generally sloping surface, one can say that for every 100 mb decrease in the surface pressure on a track from Byrd station to Amundsen–Scott the total annual moisture transport will be decreased by a factor of two. Since the mean pressure difference between Byrd and Amundsen–Scott is 126 mb, the moisture transport at Amundsen–Scott will be roughly 40% of that at Byrd. In the present case that would be $0.12 \times 10^{18}$ gm/year, which somewhat exceeds the amount necessary for a mean precipitation rate of 5 cm/year computed previously. The mean precipitation rate may be greater than 5 cm/year however, and the computed transport value at Amundsen–Scott is a slight overestimate because the simple model that has been postulated above is not strictly correct. It does not, for example, take into account the fact that some moisture will be advected through the sides of the volume extending inland from Byrd and so will be lost as far as this analysis is concerned.

Although the assumptions which underlie this simple latitudinal transport decrease model are open to question, the model itself is quite useful for rough calculations. The highest ice surface elevation in the Antarctic interior is about 4000 m (550 mb) which, if it were uniformly applicable to the Amundsen–Scott–Vostok–Plateau area, would reduce the moisture transport to 10% of that at Byrd, and produce a mean annual precipitation value of about 1 cm. This value is so small that it appears very unlikely that the ice sheet could maintain itself at such an altitude for very long before wind-produced ablation and the outward movement of the ice sheet would initiate a thinning process. The existence of an appreciably thicker ice sheet than the present one seems therefore excluded on meteorological grounds.

This conclusion of course assumes a climate not much different from the present one. Climatic amelioration does occur and should be considered in any discussion of such a slow process as the variation in thickness of the interior ice sheet. In general, the moisture transport will vary directly with the temperature, although the atmospheric mass flux may change with the climate and must also be considered. It should be noted however, that an increase in the mean temperature, for example, must occur at least throughout the troposphere for the moisture transport to increase by a noticeable amount, and that climatic variations which are confined to the surface layers will have a negligible effect on the mass balance of the ice.

## Résumé

La magnitude du transport de vapeur de l'eau dans l'intérieure de l'Antarctique par l'atmosphère est detérminée par une modèle du transport de masse qui permette une variation longitudinale en le valeur de la fluxe annuelle. Il est indiqué que l'usage des moyennes mensuelles en le transport et la température sousestime le transport annuel de vapeur de l'eau exigés par les valeurs observés de l'accumulation de glace en l'intérieure. Par suite il faut que la plupart du transport annuel de vapeur de l'eau se trouve avec les déviations positives de la température à partir des moyennes mensuelles. On examine ce rapport pour le station Byrd où on trouve qu'en été austral 1957–8 l'espace de trois jours a la température la plus grande à 700 mb produisée à peu près 20% du transport annuel de vapeur de l'eau. On examine aussi le variation altitudinal du transport de vapeur de l'eau et on discute en peu de mots son effet comme constrainte sur la élévation centrale que peut atteindre la mer de glace.

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## ПЕРЕНОС ВЛАГИ ВО ВНУТРЕННИЕ ОБЛАСТИ АНТАРКТИКИ

Определяется величина переноса влаги в атмосфере внутрь Антарктики путем использования модели переноса массы, которая учитывает долготные изменения в годовых величинах потоков. Указано, что использование среднемесячных значений переноса массы и температуры занижает годовой перенос влаги, требуемый наблюдаемыми значениями аккумуляции во внутренних областях. Следовательно, существенная часть годового переноса влаги должна происходить при наличии положительных отклонений температуры от среднемесячных значений. Эта связь проверялась для станции Бэрд, где было найдено, что в течение лета 1957–58 гг. для трех дней с наибольшими температурами на поверхности 700 *мб* перенос влаги составил почти 20% от годового переноса. Исследуется изменение переноса влаги с высотой и кратко обсуждается ограничительное его влияние на максимальную высоту, которой может достичь ледяной покров.