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MOISTURE BUDGET IN THE ANTARCTIC ATMOSPHERE

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Abstract: Climatologies of moisture flux, its convergence and accumulation rate for the Antarctic region are derived from the 5-year (1986-1990) twice-daily U.S. NMC (National Meteorological Center) objective analysis data. Over the Southern Ocean, eastward moisture flux is dominant, while westward flux exists along the Antarctic coastline. The annual mean moisture flux convergence (accumulation rate) is positive along the coastline; the maximum of 3 mm/day is found on the west coast of the Antarctic peninsula, while it is small inland. The estimated annual accumulation over Antarctica is 135 ± 18 mm. As for the seasonal variation, the accumulation is large in winter along the coast and over Antarctica as a whole, while it is large in summer in the inland elevated region.

1. Introduction

Accumulation rate (precipitation minus evaporation) on the Antarctic ice sheet is an important factor for mass balance of the Antarctic ice sheet. However, meteorological measurements of precipitation and evaporation are very difficult in Antarctica (BROMWICH, 1988). The accumulation rate has been estimated from surface glaciological measurements (GIOVINETTO and BULL, 1987), though the spatial coverage of the measurements is not enough. From atmospheric data, the accumulation rate can be estimated as a residual of the atmospheric moisture budget. BROMWICH (1979, 1988, 1990) estimated the accumulation rate for East Antarctica from rawinsonde data. MASUDA (1990) also estimated the accumulation rate for the Antarctic region (poleward of 70°S) using ECMWF (European Centre for Medium-range Weather Forecast) analysis data during the period from December 1978 to November 1979 (one year).

In the present paper, climatologies of moisture flux, its divergence and accumulation rate are derived using the 5-year (1986-1990) NMC objective analysis data. The moisture flux itself is an important variable for understanding mass transport processes over Antarctica.

2. Data and Method

Data used in this study are the twice-daily objective analysis data of the U.S. National Meteorological Center (NMC) for 5 years during the period from 1986 through 1990. The horizontal resolution of the data is 2.5° by 2.5°. The data contain relative humidity at 6 standard levels (1000, 850, 700, 500, 400, 300 hPa); wind, temperature and geopotential height data have 6 more levels above 300 hPa.

The mixing ratio of water vapor (q) is calculated at each level, using the Tetens formula, from relative humidity and temperature data. The surface pressure is calculated by linear interpolation from geopotential height and topography data. The topography data are constructed from 0.2° by 0.25° global topography data. The mixing ratio and wind data are interpolated to 10 hPa intervals by a cubic spline function. These interpolated data are used for the vertical integration mentioned later.

The moisture budget equation is written as follows:

$$\frac{\partial q}{\partial t}+\nabla\cdot q\boldsymbol{V}+\frac{\partial}{\partial p}(q\omega)=Source-Sink, \tag{1}$$

where $\boldsymbol{V}$ is the horizontal wind vector, p is pressure and ω is vertical p-velocity. By integrating eq. (1) vertically from the surface (p_s) to top (p_t) and using a pressure tendency equation, we obtain

$$\frac{\partial}{\partial t}\int_{p_t}^{p_s} q\ \mathrm{d}p + \nabla\cdot\int_{p_t}^{p_s} q\boldsymbol{V}\ \mathrm{d}p=\int_{p_t}^{p_s} Source\ \mathrm{d}p-\int_{p_t}^{p_s} Sink\ \mathrm{d}p. \tag{2}$$

The vertical integrals of *Source* and *Sink* are proportional to evaporation (or sublimation) and precipitation, respectively. The top is set to be at 300 hPa because there are no available data. The error due to omission of the upper level does not affect the results significantly because moisture is negligible above 300 hPa. Precipitable water and total moisture flux vector are defined as follows:

$$Q_{\mathrm{T}} \equiv \int_{p_t}^{p_s} q\,\frac{\mathrm{d}p}{g}, \tag{3}$$

$$\boldsymbol{Q}_{\mathrm{V}} \equiv \int_{p_t}^{p_s} q\boldsymbol{V}\,\frac{\mathrm{d}p}{g}, \tag{4}$$

where g is the acceleration of gravity. By integrating eq. (2) with time from 0 to t and using definitions (3) and (4), we obtain

$$\frac{1}{t}\,(Q_{\mathrm{T}}\,(t)-Q_{\mathrm{T}}\,(0))+\overline{\nabla\cdot\boldsymbol{Q}_{\mathrm{V}}} = \overline{E_v - P_r}, \tag{5}$$

or

$$\overline{P_r - E_v} = -\frac{1}{t}\,(Q_{\mathrm{T}}\,(t)-Q_{\mathrm{T}}\,(0))-\overline{\nabla\cdot\boldsymbol{Q}_{\mathrm{V}}}, \tag{5$'$}$$

where the overbar denotes time average, P_r is precipitation and E_v is evaporation. Thus "P_r minus E_v" can be derived from change of precipitable water and moisture flux divergence.

3. Results

3.1. Precipitable water at Syowa Station

The quality of the NMC data is first checked by comparing with observations at Syowa Station (69°00′S, 39°35′E). Figure 1 shows the monthly mean precipit-

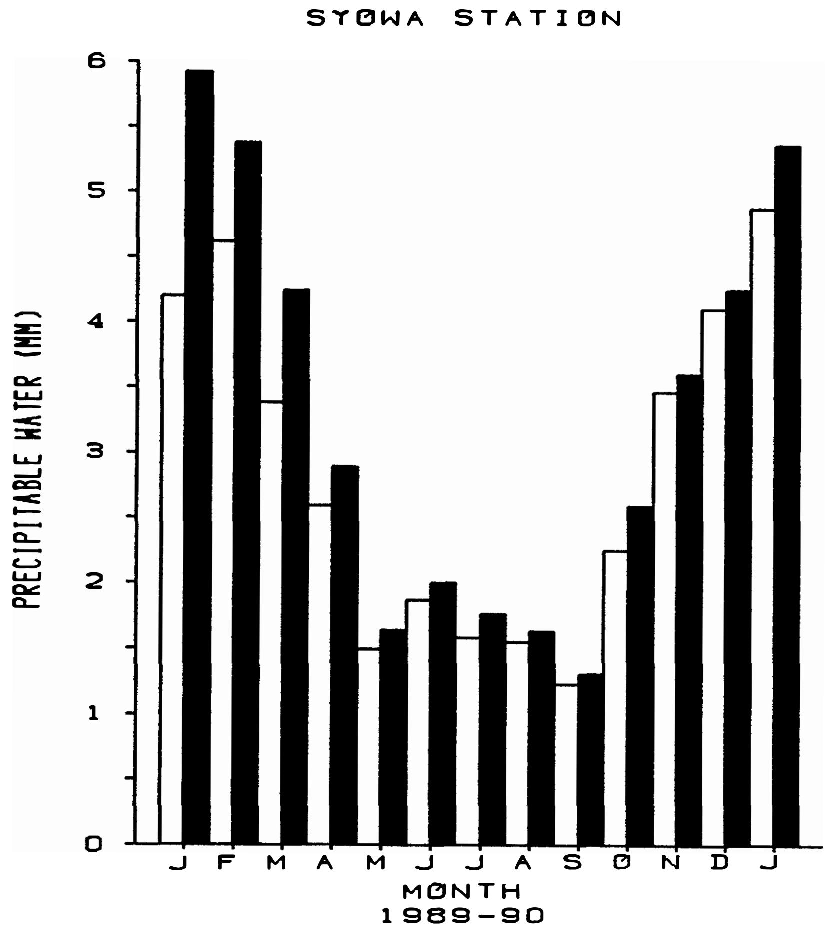

Fig. 1. White bars: monthly mean precipitable water at Syowa Station during the period from January 1989 to January 1990 derived from the NMC data. Black bars: same as the white bars but for rawinsonde data.

able water (white bars) at Syowa Station during the period from January 1989 to January 1990 derived from the NMC data. The values are obtained by linear interpolation from surrounding grid point values. Also shown are the corresponding observations (black bars) at Syowa Station (WADA, 1991, personal communication). The precipitable water attains its maximum in summer; it is small during winter. Two minima appear in May and September, and a small peak is found in June. This seasonal variation is well represented by the NMC data. However, the NMC data systematically underestimate the precipitable water. The average value of the NMC data is about 13 % lower than the observations. The spatial variation of precipitable water near Syowa Station is very large. Taking the large spatial variation into account, the agreement with the observations is satisfactory.

3.2. Moisture flux

The 5-year and seasonal mean moisture flux is shown in Fig. 2 for the Antarctic region. Also the annual mean is shown in Fig. 3. Throughout the year,

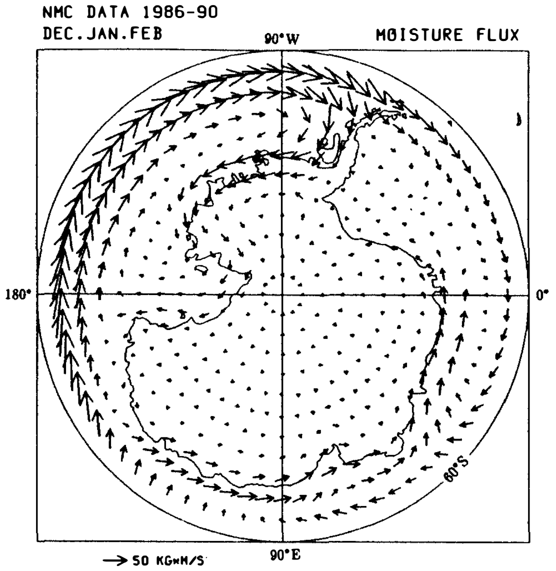

Fig. 2a. *5-year (1986–1990) mean moisture flux for summer (December, January and February) computed from the NMC data. A scale of arrows is shown at the bottom.*

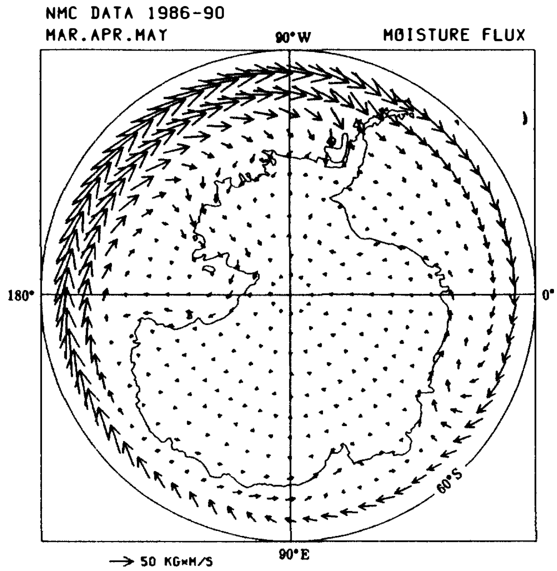

Fig. 2b. *Same as in Fig. 2a except for fall (March, April and May).*

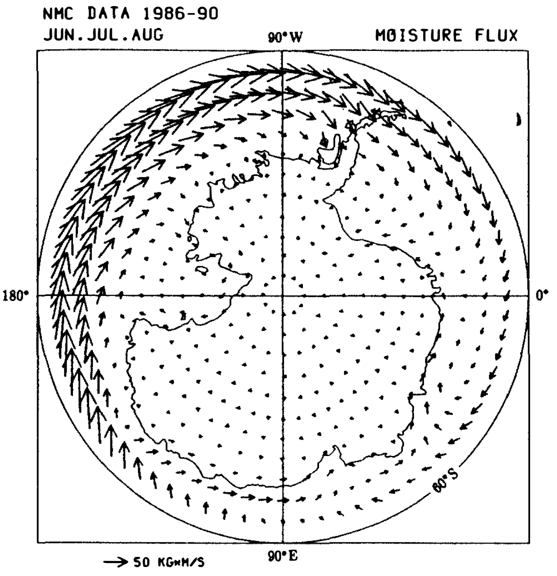

Fig. 2c. *Same as in Fig. 2a except for winter (June, July and August).*

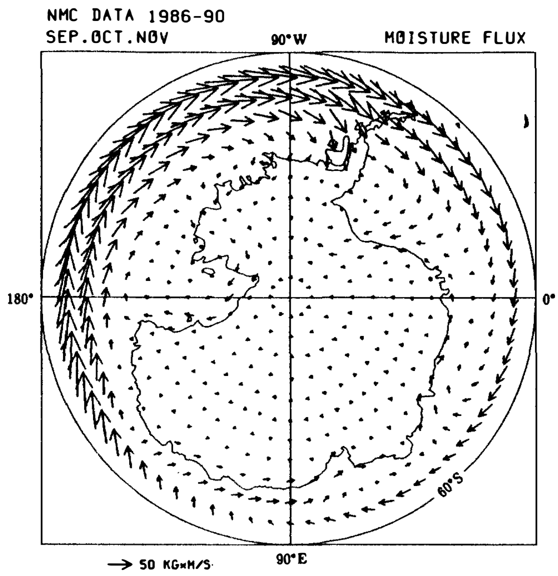

Fig. 2d. *Same as in Fig. 2a except for spring (September, October and November).*

large eastward (westerly) moisture flux is present over the Southern Ocean. In particular, the flux is large from 135°E to 45°W (clockwise). Along the coastal region, the moisture flux is generally parallel to the coastline. In summer (December, January and February), westward (easterly) moisture flux is dominant along the coastline of Antarctica. This flux is weak in other seasons. In summer, strong poleward flux is found along the westside of the Antarctic peninsula and west coast of West Antarctica. In other seasons, these poleward

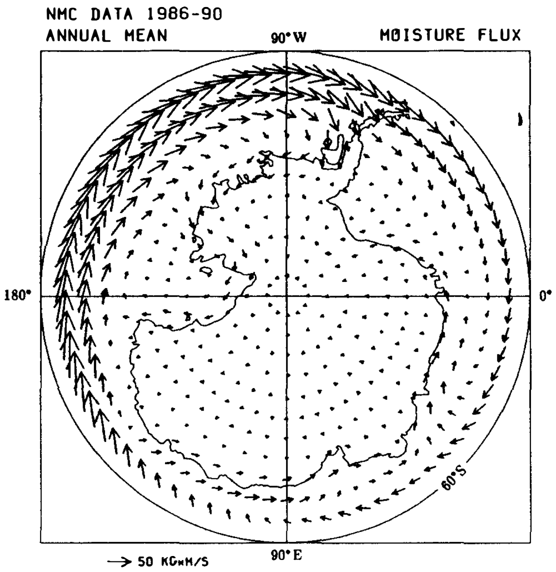

Fig. 3. Same as in Fig. 2a except for annual mean.

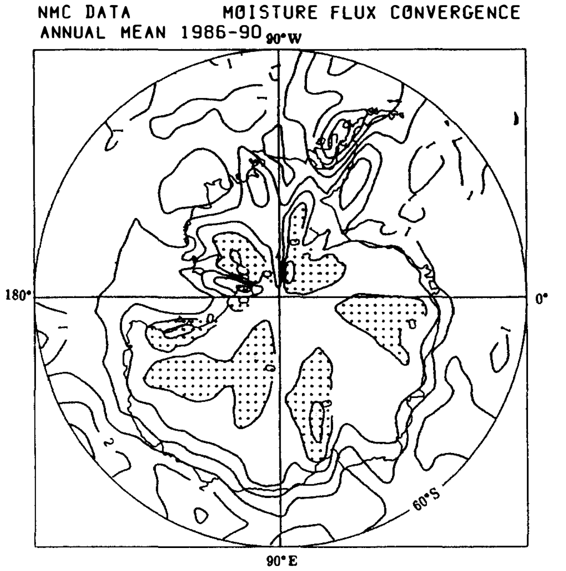

Fig. 4. Annual mean moisture flux convergence derived from the NMC data. Contour intervals are 0.5 mm/day. Negative values are dotted.

fluxes become weak. In winter and spring, strong poleward flux appears over the Weddell Sea. Around Syowa Station, the moisture flux is poleward and westward throughout the year. In the inland region of Antarctica, the moisture flux is very small. BROMWICH (1979, 1988) calculated annual moisture flux for East Antarctica based on rawinsonde observations for 1972. The strong poleward flux around 45°E is seen both in BROMWICH's result and the present result (Fig. 3). In general, both studies agree quite well.

3.3. *Moisture flux convergence*

The 5-year mean moisture flux convergence is shown in Fig. 4. Because moisture flux convergence is a derivative of the moisture flux, the derived field is noisy. Therefore, spatial smoothing is applied to the original field in Fig. 4. Since the averaging period is long enough, the first term on the r.h.s. of eq. (5)′ (rate of change of precipitable water) is negligible. Therefore, the moisture flux convergence is equal to P_r minus E_v, which is the accumulation rate of snow over the Antarctic ice sheet when the redistribution of snow by drift is neglected. Over the Southern Ocean, P_r minus E_v is positive and has values about 1–2 mm/day. Over Antarctica, values are large along the coast. In particular, the maximum value of about 3 mm/day is calculated at the west coast of the Antarctic Peninsula. Values greater than 1 mm/day are found at the coastline of West Antarctica, the head of the Ross Sea, and the coast of Wilkes Land. These features roughly accord with the observation of surface mass balance of Antactic ice sheet (GIOVINETTO and BULL, 1987). However, there are several spotty negative regions inside Antarctica. These negative values seem to be unrealistic, though the negative regions generally correspond to very small accumulating regions (GIOVINETTO and BULL, 1987).

3.4. *Accumulation rate over Antarctica*

Following eq. (5)′, the areal mean accumulation rate (P_r minus E_v) is calculated over Antarctica for each month (Fig. 5). For one month periods, the rate of change of precipitable water is one order smaller than the moisture flux convergence. The annual average is 135 mm/year and the standard deviation (S.D.) is 18 mm/year. This value is very close to the value of 143 mm/year that is obtained by GIOVINETTO and BULL (1987). By estimating drift snow loss and surface run-off, BROMWICH (1990) corrected the above value to 151–156 mm/year for P_r minus E_v. This corrected estimate is within the range of the present study (see Table 1). The accumulation rate is low in early summer. A weak semi-annual oscillation, which has peaks in spring and early fall, is present.

Figure 6 is similar to Fig. 5 except for the region poleward of 70°S. Because this region contains oceanic grid points, the values are larger than those in Fig. 4. The annual average is 162 mm/year and the standard deviation is 19 mm/year. MASUDA (1990) obtained 148 mm/year for the period from December 1978 to November 1979 using the ECMWF analysis data. Both results agree within the interannual variability.

Both annual and semi-annual oscillations are seen in the present study. In both regions (Figs. 5 and 6), the rate is generally larger in the cold season than

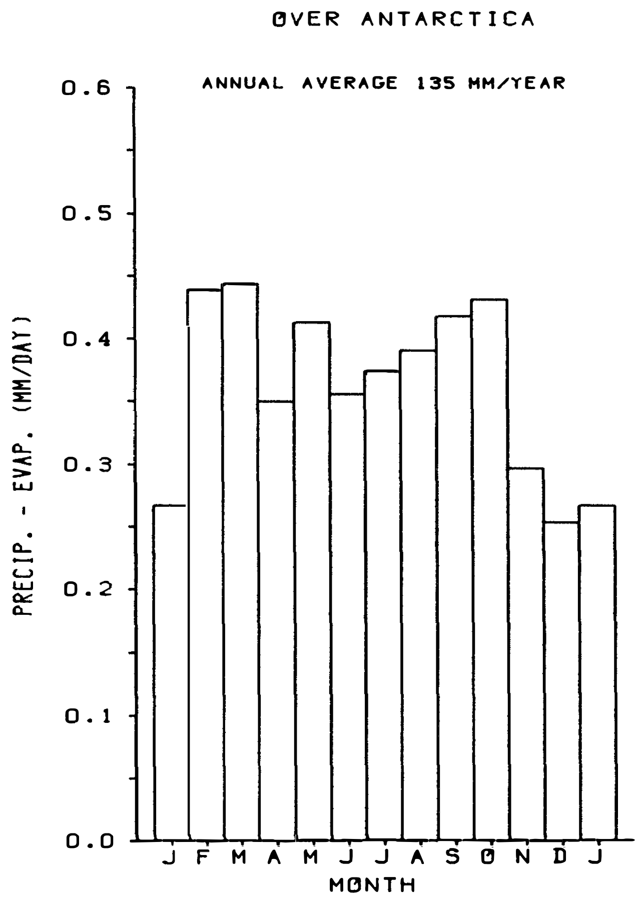

Fig. 5. Monthly mean accumulation rate (P_r minus E_v) for Antarctica derived from the NMC data.

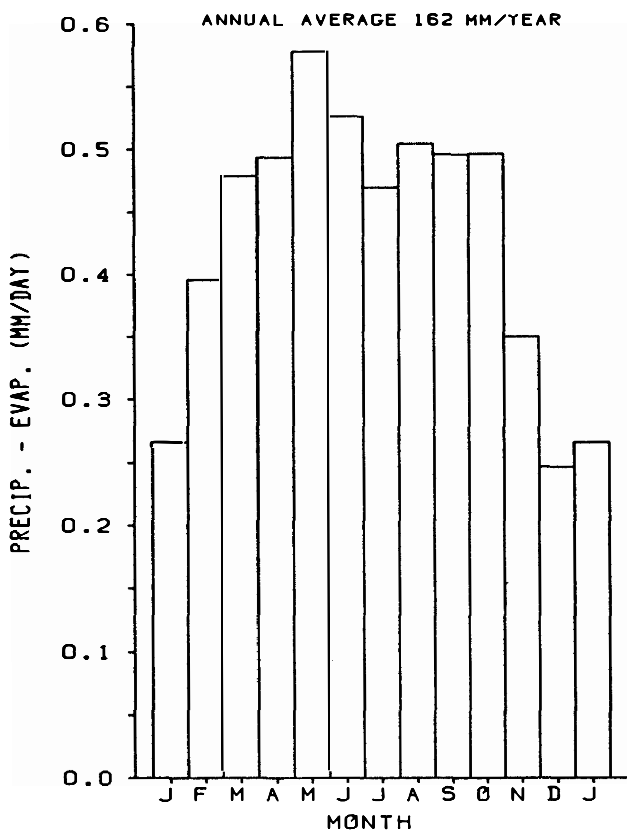

Fig. 6. *Same as in Fig. 5 except for the region poleward of 70°S.*

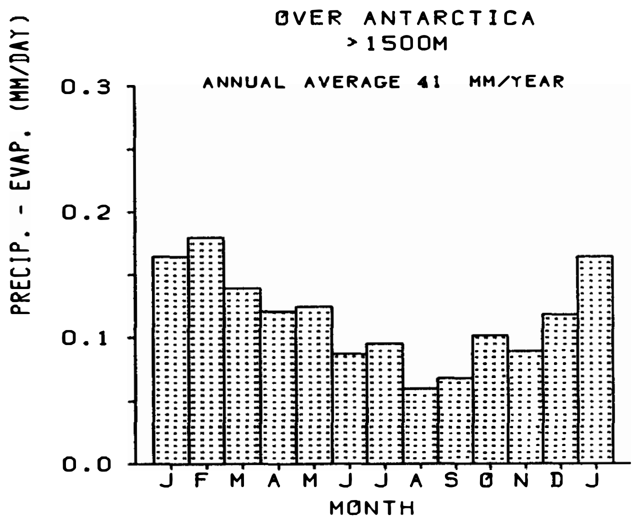

Fig. 7. *Same as in Fig. 5 except for the Antarctic region where the elevation is greater than 1500 m.*

in the warm season. The observations show that the circumpolar cyclone activity is generally intense during winter and it exhibits a semi-annual oscillation with peaks in spring and fall. Coastal precipitation is episodic in association with cyclone activities. For the whole Antarctic region, the contribution from the

Table 1. Estimated annual accumulation (mm).

Year	Poleward of 70°S	Antarctica	Antarctica (>1500 m)
1986	152	132	58
1987	139	124	49
1988	180	148	42
1989	183	158	33
1990	155	114	25
Mean	162	135	41
S.D.	19	18	13

interior of Antarctica is small. Therefore, the seasonal variation of the accumulation rate over Antarctica seems to be controlled by cyclone activity. It is interesting that the accumulation rate is large during the cold season when the precipitable water is low.

Figure 7 is the same as Fig. 5 except for the region where the elevation is greater than 1500 m. Even in this inland region, the areal mean accumulation rate is positive throughout the year. The annual mean rate is 41 mm/year and the standard deviation is 13 mm/year. The rate is much smaller than the average over the whole of Antarctica. The rate is large in summer and small in winter. This seasonal variation is almost opposite to that over the whole of Antarctica, and it parallels the seasonal variation of temperature.

The estimated annual mean accumulation rates for various regions are summarized in Table 1.

3.5. Accumulation rates at Syowa and Mizuho Stations

WADA (1991, personal communication) made radar observations at Syowa Station and estimated precipitation (snowfall) there from a *Z–R* relation. Figure 8 presents the comparison of the observed precipitation rate and P_r minus E_v derived from the NMC data for 1989. In principle, the two values should not agree, because of evaporation, though the evaporation is probably smaller than the precipitation. The annual observed precipitation is 391 mm, while P_r minus E_v is 288 mm in 1989. As a crude estimate, the annual precipitation at Syowa station in 1989 was 400 mm and the evaporation 100 mm.

KOBAYASHI (1985) estimated the precipitation at Mizuho Station (70°42′S, 44°20′E, 2230 m above sea level) from drifting snow measurements. The estimated annual precipitation was 140 mm in 1980. TAKAHASHI (1985) also estimated the precipitation at Mizuho Station using two different methods. The estimated values in 1982 were 230 and 260 mm. FUJII and KUSUNOKI (1982) reported that the annual amounts of sublimation and condensation in 1977 were estimated to be 54 mm and 6 mm, respectively. Hence the net sublimation was 48 mm in 1977. Therefore, the annual accumulation rate at Mizuho Station is about 90–210 mm. On the other hand, 5-year annual P_r minus E_v at Mizuho is estimated as 201 mm from the NMC data. The present estimate seems to be reasonable by taking into account the uncertainty due to observational and methodological errors and interannual variability.

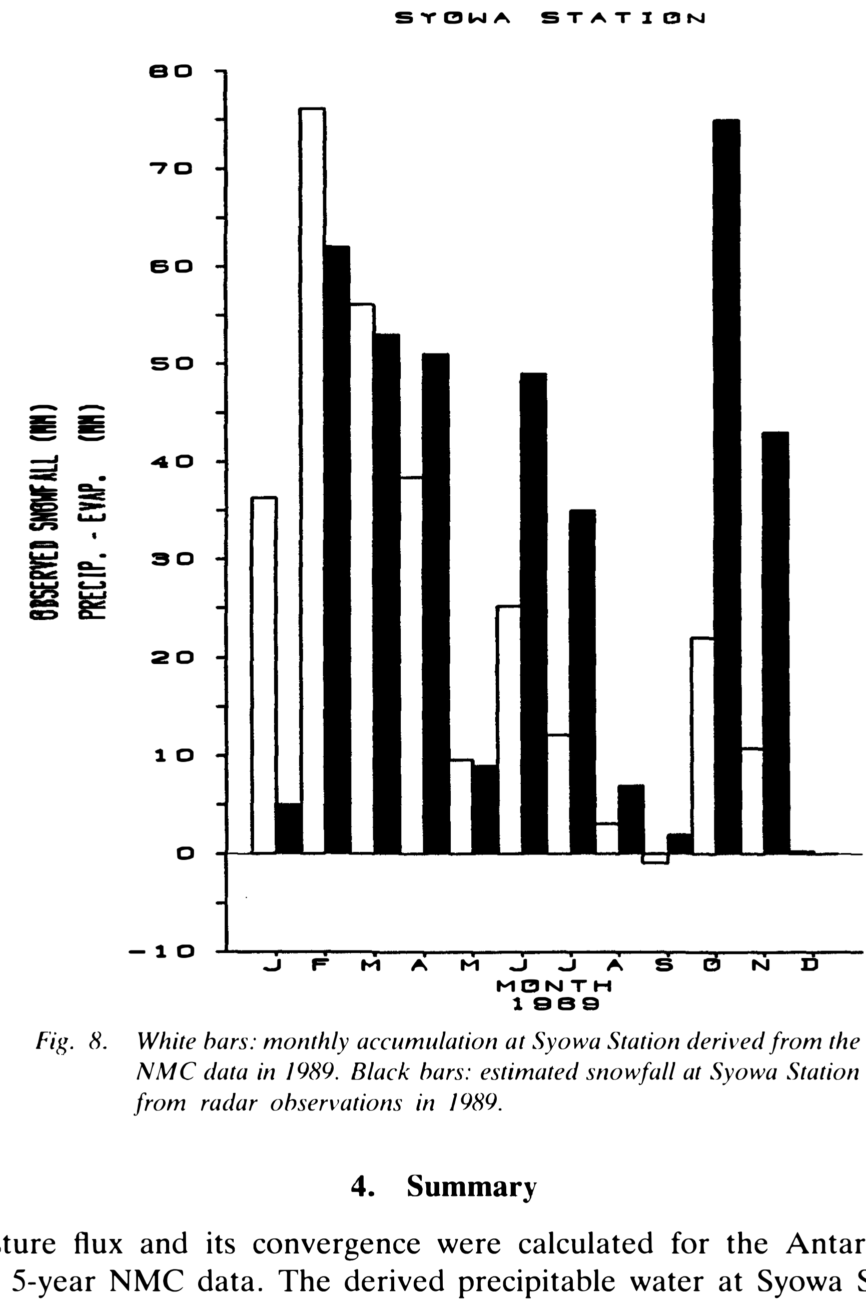

Fig. 8. White bars: monthly accumulation at Syowa Station derived from the NMC data in 1989. Black bars: estimated snowfall at Syowa Station from radar observations in 1989.

4. Summary

Moisture flux and its convergence were calculated for the Antarctic region using the 5-year NMC data. The derived precipitable water at Syowa Station was compared with rawinsonde observations; agreement was satisfactory. Eastward moisture flux is dominant over the Southern Ocean, while westward moisture flux exists along the Antarctic coastline. Over the Southern Ocean, the moisture flux convergence is positive and has values about 1–2 mm/day. Over Antarctica, values are large along the coast; values greater than 1 mm/day are obtained in some regions. Values as large as 3 mm/day are obtained on the west coast of the Antarctic Peninsula. Inside Antarctica, values are small; negative values appear in some spotty regions. The annual accumulation (P_r minus E_v) is 135±18 mm (0.37±0.05 mm/day) over Antarctica. As for the seasonal variation of accumulation rate, it is large in winter along the coast and over Antarctica as a whole, while it is large in summer in the high-elevation region.

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