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ATMOSPHERIC HEAT AND WATER BUDGETS OF POLAR REGIONS: ANALYSIS OF FGGE DATA

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Abstract: Monthly and annual budgets of energy and water in the atmosphere are calculated for the two polar caps, northward of 70°N and southward of 70°S. FGGE (First GARP Global Experiment) IIIb data produced by ECMWF (European Centre for Medium-Range Weather Forecasts) are used. For the north polar cap, reasonable results are obtained, confirming an independent analysis by N. NAKAMURA and A. H. OORT (J. Geophys. Res., **93**, 9510, 1988). For the south polar cap, large uncertainty remains in the estimation of advective transport due to the mean meridional circulation.

1. Introduction

To understand climatic change, we have to consider a coupled system which consists of the ocean, the cryosphere and the atmosphere. Among these subsystems, observations are made most frequently in the atmosphere. Therefore, the total energy and water budgets of the atmosphere are useful not only for research of the atmosphere but also for the research of the cryosphere and ocean. In the polar regions, current post-glacial climate maintains Antarctic and Greenland ice sheets in a nearly steady state. Unfortunately, budget analyses of the atmospheric variables do not have sufficient accuracy to determine whether the ice sheets are expanding or retreating in the long run. They can show, however, seasonal variation of exchange of energy and that of water between the ice sheets and the atmosphere, which gives some hint to the understanding of maintenance of the ice sheets and their possible response to the other components of climate.

Two methods have been practiced for budget analyses of the global atmosphere (LAU and OORT, 1981). What they call "Scheme A" is to calculate time averages and covariances of atmospheric variables (wind velocity, temperature, etc.) at each observing station, and then to interpolate them to regularly spaced gridpoints. "Scheme B" is to spatially interpolate variables at each time step to be analyzed (usually once or twice a day), and perform time series analyses at gridpoints.

Recently, NAKAMURA and OORT (1988: abbreviated here as NO88) did an atmospheric energy budget analysis of polar caps. They used atmospheric general circulation statistics for 1963–73 by OORT (1983), which are based on "Scheme A" mentioned above. For radiation flux at the top of the atmosphere, they used CAMPBELL and VONDER HAAR's (1980) composite of many satellite observations during 1966–77. The result of NO88 was satisfactory for the north polar cap (NPC), but the calculated mean meridional circulation was presumably unrealistic for the south polar cap (SPC). Consequently, they replaced the results for the SPC with that of simulated climate in the atmospheric general circulation model of MANABE and HAHN (1981). N. NAKAMURA and A. H. OORT (pers. commun.) provided additional analysis (abbreviated here as NO+) of advective fluxes based on OORT (1983)*.

For actual application of "Scheme B", time extrapolation by forecast models is necessary in addition to spatial interpolation of observations. Until 1979, nearly all general circulation studies with this approach used operational gridpoint products which were produced in real-time in order to provide initial condition for numerical weather prediction. For the one-year period of the First GARP Global Experiment (FGGE), special gridpoint data sets, called "FGGE level IIIb data sets", were produced, which benefited from delayed reports as well as real-time ones. The present study employs one of the FGGE IIIb data sets which was produced by the European Centre for Medium-Range Weather Forecasts. Both energy and water balance will be shown.

The results are not discussed in detail here. The energy budget essentially confirms that presented in to NO88 paper. The interpretation of the water budget is still premature.

2. Formulation of the Problem

Following NAKAMURA and OORT (1988), we consider the energy budget of the atmosphere in two boxes surrounded by hypothetical vertical walls at 70° latitudes North and South (see Fig. 1a). The small contribution of kinetic energy being neglected, the energy balance can be written as

$$\frac{\Delta\langle E\rangle}{\Delta t}=F_{\mathrm{rad}}+F_{\mathrm{adv}}+F_{\mathrm{sfc}}\,. \tag{1}$$

Here, Δ denotes differences in a unit time interval Δt (=a month in the present study).

$$\langle E\rangle=\frac{1}{A}\iint_{p\mathrm{top}}^{p_{\mathrm{s}}}\{C_{\mathrm{v}}T+gz+Lq\}\frac{\mathrm{d}p}{g}\mathrm{d}A$$

is the total energy of the atmosphere in the hypothetical box, divided by the area of

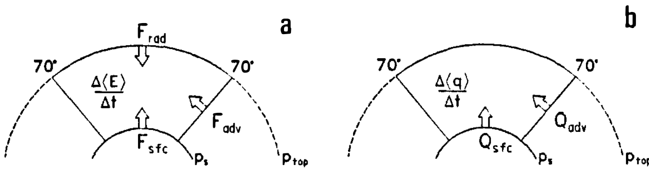

Fig. 1. (*a*) *Schematic diagram of energy budget for a polar cap* (*modified from NAKAMURA and OORT, 1988*). (*b*) *Schematic diagram of water budget for a polar cap.*

* There is a minor difference between NO+ and NO88. In calculating transport terms by time-mean fields, NO+ used annual statistics, and averaged the values for all ten years. NO88 used mean fields over ten years. Therefore, the transport due to interannual correlation of variables was included in MMC and SE terms in NO+, and in TE terms in NO88 (definitions of MMC, SE and TE are described in Section 2).

the polar cap, A. F_{rad} is the net radiative flux per unit area at the top of the atmosphere.

$$F_{adv}=\pm\frac{1}{A}\int_0^{2\pi}\int_{ptop}^{ps}\{(C_pT+gz+Lq)v\}\frac{dp}{g}a\cos 70°\,d\lambda$$

is the total horizontal advection of moist static energy across the 70° latitude circle into the polar cap, divided by the area of the polar cap. The sign in the formula is positive for NPC and negative for SPC. (NO88 called this term "F_{wall}".) F_{sfc} is the net energy flux density from the surface (land, sea or ice) to the atmosphere.

Similarly, the budget of atmospheric water vapor in the atmosphere is written as follows (see Fig. 1b).

$$\frac{\Delta\langle q\rangle}{\Delta t}=Q_{adv}+Q_{sfc}\,. \tag{2}$$

In this formula,

$$\langle q\rangle=\frac{1}{A}\iint_{ptop}^{ps}q\frac{dp}{g}dA$$

is the vertically integrated area mean moisture content. (q is specific humdity.)

$$Q_{adv}=\pm\frac{1}{A}\int_0^{2\pi}\int_{ptop}^{ps}qv\frac{dp}{g}a\cos 70°\,d\lambda$$

is the total horizontal advection of water vapor across the 70° latitude circle into the polar cap, divided by the area of the polar cap. Q_{sfc} is the net water flux density from the surface, that is, the difference between evaporation and precipitation. (Here, horizontal transport of condensed water is neglected.)

$\langle E\rangle$, $\langle q\rangle$, F_{adv} and Q_{adv} can be evaluated with meteorological data. F_{rad} is observed by satellites. Accordingly, F_{sfc} and Q_{sfc} can be estimated as residuals.

For the further discussion of advective terms, let us introduce the following notation:

$\overline{(\ )}$: time mean (monthly mean in the present study);
$(\ )'$: deviation from time mean;
$[(\ )]$: zonal mean;
$(\ )^*$: deviation from zonal mean.

Time mean values of F_{adv} and Q_{adv} involves $[\overline{hv}]$ (where $h=C_pT+gz+Lq$) and $[\overline{qv}]$, respectively. $[\overline{hv}]$ can be decomposed as

$$[\overline{hv}]=[\bar{h}][\bar{v}]+[\bar{h}^*\bar{v}^*]+[\overline{h'v'}]\,. \tag{3}$$

Here we will follow the conventional naming of the terms on the right-hand side: the mean meridional circulation (MMC), stationary eddies (SE) and transient eddies (TE). They could be more rigorously called the stationary axi-symmetric component, the stationary asymmetric component and the non-stationary component, respectively. The decomposition of $[\overline{qv}]$ is done in a similar way.

3. Data and Analysis Method

For $\langle E \rangle$, F_{adv}, $\langle q \rangle$ and Q_{adv}, the FGGE "main" IIIb data produced by ECMWF (European Centre for Medium-Range Weather Forecasts) are used. The method of data assimilation is described by BENGTSSON *et al.* (1982). The period of observations are from 1 December 1978 to 30 November 1979. The horizontal resolution is 1.875° latitude × 1.875° longitude. In the vertical, data are given at 15 levels between 10 hPa and 1000 hPa.

In the present study, monthly mean statistics are computed from the original twice-daily gridpoint data. The upper boundary p_{top} is placed at the 50 hPa level, and the lower boundary p_{s} is the pressure interpolated to the ground surface of the ECMWF forecast model. For details, see MASUDA (1988b). The advective fluxes calculated at the grid row of 69.375° latitude are considered to represent those at the "wall" at 70°.

The advantages of FGGE data compared with OORT's (1983) statistics are as follows.

* Physically-based space-time extrapolation by forecast models is used. ("Scheme A" uses interpolation just in the space domain.)
* Observations made by moving platforms (satellites, aircrafts, buoys, etc.) are utilized. (OORT used only rawinsonde station observations and surface ship observations.)
* The observing network was enhanced during the FGGE period, especially in the tropics and over the southern ocean.

Their disadvantages are as follows.

* The duration of FGGE was only one year. (OORT used ten years' data during 1963–1973.)
* The gridpoint fields are dependent not only on observations but also on the physical assumptions of forecast models.

As discussed in MASUDA (1988a), the gridpoint data of FGGE do not necessarily satisfy conservation of mass. The error is large over sloping terrain. A probable source of this inconsistency is vertical interpolation of variables between "sigma" and pressure coordinates. The vertical distribution of this kind of error is unknown. Also, the inconsistency can be partly due to observational error. In case of rawinsonde observations, error is larger at higher altitudes. Since satellite observations are also used, the distribution of error may be different. Because of lack of information, we simply assume that the magnitude of error in wind velocity is independent of altitude. In the present study, mass-weighted vertical averages of divergent wind components are subtracted from the wind fields before calculating transports (see MASUDA, 1988b, for details). For the application described here, this has practically the same effect as subtracting mass-weighted vertical mean from the zonally averaged meridional component of winds ($[v]$) as done by NAKAMURA and OORT (1988).

For F_{rad}, the observation during the one-year period of FGGE by the Earth Radiation Budget (ERB) Narrow Field of View (NFOV) instrument of the Nimbus 7 satellite is used. Data for monthly mean net radiation are extracted from the

MATRIX tape. The global and annual mean value of net radiation, -3.164 W m^{-2}, is subtracted from values at every grid box, because it can be assumed that it represents the bias of the observing equipment. The contributions of grid boxes partly incorporated in the polar caps are accounted for in proportion to area.

The advantages of the ERB data selected here (compared with CAMPBELL and VONDER HAAR's (1980) compilation used by NO88) are more accurate instrumentation with broader spectral bands, and coincidence with atmospheric observations of FGGE. Disadvantages are the shorter duration and the fact that the passage of the satellite does not cover all phases of diurnal variation.

4. Energy Budgets

Monthly values of terms of eq. (1) are displayed in Fig. 2 and Fig. 3 for NPC and SPC, respectively. In order to place corresponding seasons at similar positions, Fig. 2 shows the annual cycle from January to January, while Fig. 3 shows the annual cycle from July to July. In these panels, solid lines are for the results of the present study. Dashed lines are for the results of NO88. Note that they used model results for F_{adv} and F_{sfc} of SPC. Dotted lines are for the results of NO+. The values from NO88 are shown after smoothing in time by a (1, 2, 1)-weighted running mean. No smoothing is applied to the values of NO+ as well as of FGGE. The decomposition of F_{adv} into MMC, SE and TE is shown in Figs. 4 and 5, for NPC and SPC, respectively. In these panels, solid lines denote the present study and dotted lines denote the results of NO+. The annual heat balance is summarized in Fig. 6.

The magnitude of the term of local time change, $\Delta\langle E\rangle/\Delta t$ (Figs. 2a and 3a) is, though smaller than other three terms, not negligible in those high latitudes. In both polar caps, this term is positive in spring and negative in autumn.

The net radiation at the top of the atmosphere, F_{rad} (Figs. 2b and 3b), attains a maximum near the summer solstice. The value at this time is nearly zero in NPC and -23.4 W m^{-2} (for December) in SPC. The smaller amplitude of annual variation of this term in SPC than in NPC can be attributed to the higher surface albedo in summer and lower surface temperature in winter. Compared with NO88, F_{rad} in SPC in summer is smaller.

In NPC, the term due to advection, F_{adv}, is larger in winter than in summer (Fig. 2c). This seasonal dependence comes from MMC and SE components (Fig. 4). The surface flux term, F_{sfc} (Fig. 2d), is positive in winter and negative in summer. The annual mean value of F_{sfc} is $+4.0$ W m^{-2}. This is not an unreasonable value because sea water as well as sea ice can carry heat poleward to compensate for this loss. The difference between this value and $+2.4$ W m^{-2} in NO88, or between the present result and zero, seems to be still within the noise level. For discussion of the annual heat budget of polar ocean and cryosphere, the accuracy of F_{sfc} is not yet satisfactory.

In SPC, F_{adv} estimated from FGGE data (the solid line labeled "FGGE" in Fig. 3c) is about 50 W m^{-2} throughout the year. In wintertime, the difference between the present result and those of NO88 and NO+ is large. The present result indicates considerably smaller poleward heat advection than the general circulation model result of NO88 (dashed line), while analysis based on station data of NO+ (dotted

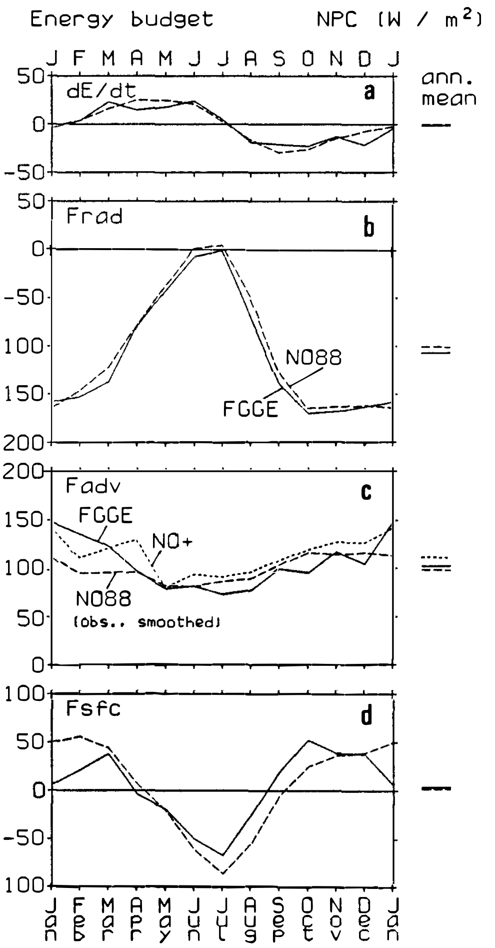

Fig. 2. Components of monthly energy budget of the north polar cap. The unit is W m^{-2}*. The horizontal lines at the right margin show the annual mean values. "FGGE", "NO88" and "NO+" stand for the present study, NAKAMURA and OORT (1988), and NAKAMURA and OORT (pers. commun.), respectively. (a) Local time change, (b) radiation, (c) advection, (d) surface fluxes.*

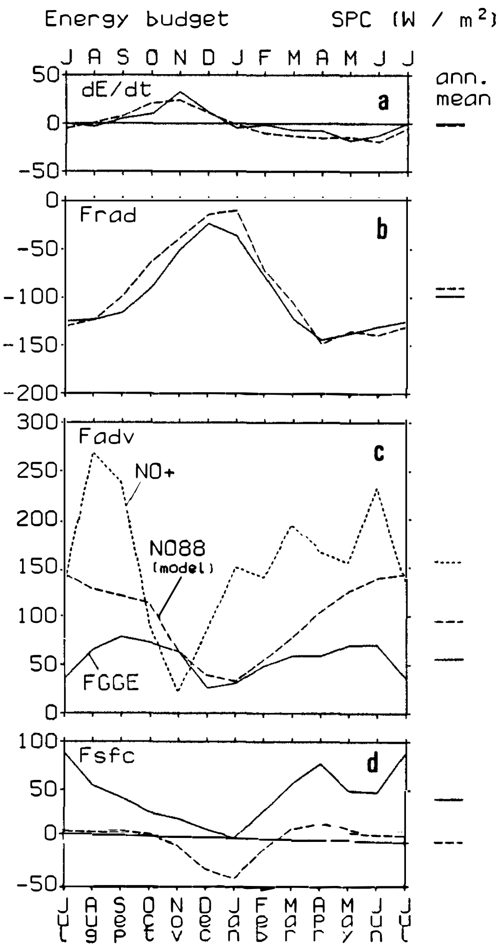

Fig. 3. Same as Fig. 2, but for the south polar cap.

line) yields much larger values. The difference comes from the MMC component (Fig. 5a). Annual mean of F_{sfc} is $+42$ W m^{-2} according to the present analysis (Fig. 6b). It is probable in reality, however, that the annual mean F_{sfc} is more than an order of magnitude smaller than this, because the ocean, which can transport heat horizontally below the surface, covers only 20% of SPC defined here, and the heat consumed by melting of ice cannot be that large. It is likely that the present analysis is biased, especially in winter, and that the MMC component of F_{adv} is actually larger, and F_{sfc} is smaller, in reality than presented here.

This bias might be due to the inconsistency of mass transport mentioned in Section 3. An order-of-magnitude demonstration will be given below. The apparent net mass transport at 70°S is about -1×10^{10} kg s^{-1} (MASUDA, 1988a, b; the negative

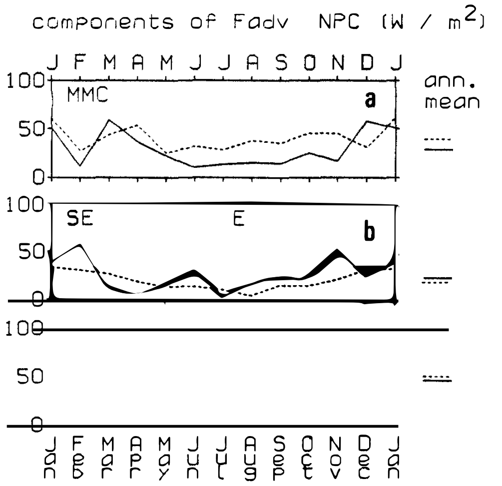

Fig. 4. *Components of the advective term of energy budget for the north polar cap. The unit is W m*$^{-2}$. (*a*) *Mean meridional circulation,* (*b*) *stationary eddies,* (*c*) *transient eddies.*

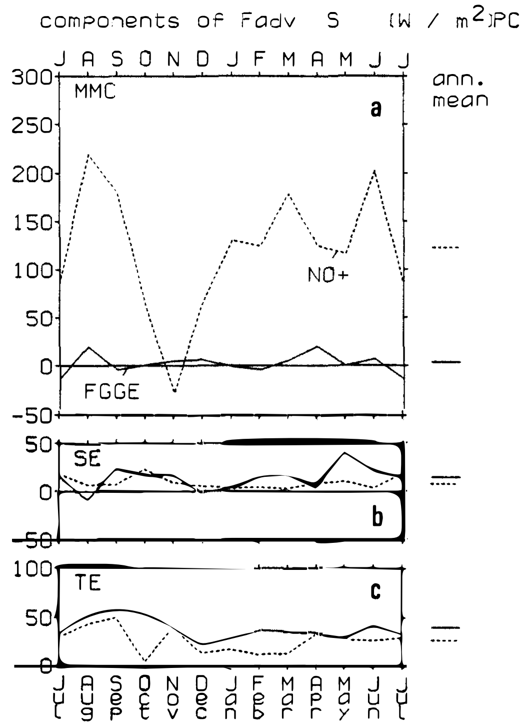

Fig. 5. *Same as Fig. 4, but for the south polar cap.*

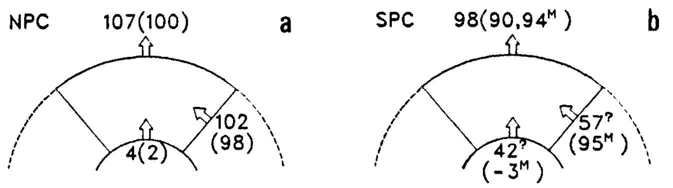

Fig. 6. *Summary of the annual mean energy budgets of polar caps. Compare Fig. 1a. Values in parentheses are from* NAKAMURA *and* OORT *(1988), "M" denotes the results from a model, and "?" stands for questionable values.*

sign indicates southward transport). If we alter only the winds near the ground instead of modifying those at all levels with equal weights, the effective vertical mean position of the adjustment will become lower by about 7 km. It can change the transport of energy across the 70°S circle by about -7×10^{14} W, thus increasing F_{adv} by about 40 W m^{-2} .This suggests the possibility that the analysis of FGGE data with usual assumptions about the adjustment of mass under-estimates the meridional-vertical overturning in the southern polar cell.

5. Water Budgets

The terms of eq. (2) are shown in Figs. 7 and 8 for NPC and SPC, respectively, according to the present analysis of FGGE data. The values actually plotted are the terms multiplied by the latent heat of vaporization of water, $L(=2.50\times10^6$ J kg$^{-1})$. This convention is for ease of comparison with monthly precipitation: 1 W m^{-2} of

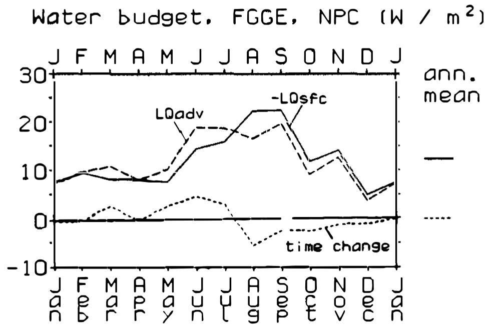

Fig. 7. Components of monthly water budget of the north polar cap resulting from FGGE data. The unit is W m^{-2}*. The horizontal lines at the right margin show the annual mean values. Dotted line: local time change; Dashed line: advection; Solid line: precipitation minus evaporation.*

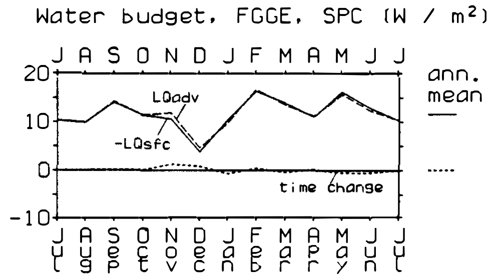

Fig. 8. Same as Fig. 7, but for the south polar cap.

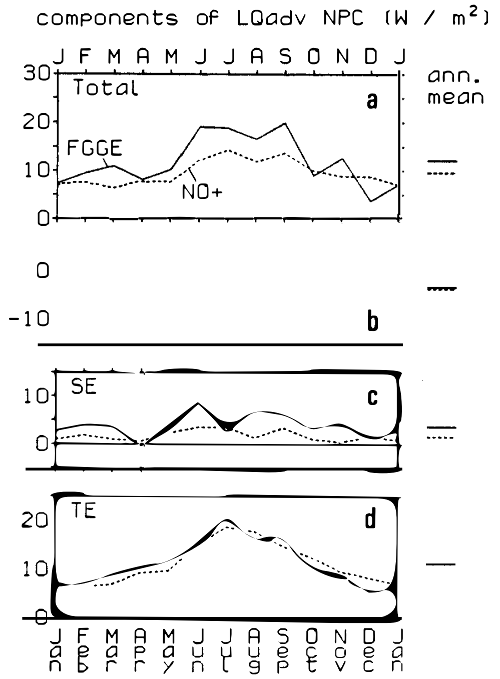

Fig. 9. Components of the advective term of water budget for the north polar cap. The unit is W m^{-2}*. Solid lines are for the present result, dotted lines are for* NAKAMURA *and* OORT *(pers. commun.). (a) Total, (b) mean meridional circulation, (c) stationary eddies, (d) transient eddies.*

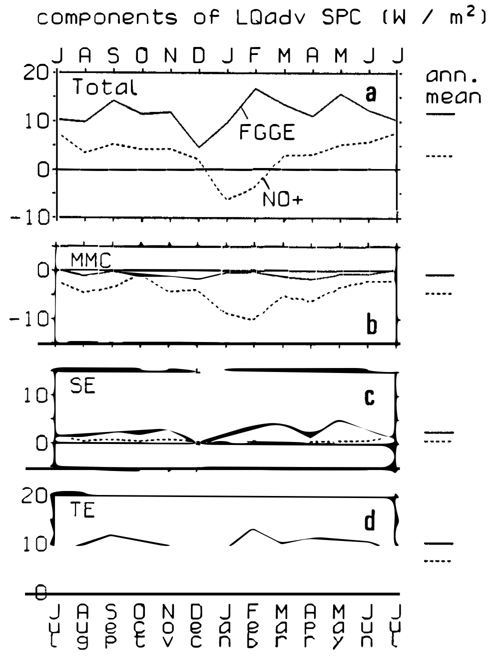

Fig. 10. Same as Fig. 9, but for the south polar cap.

$-LQ_{\rm sfc}$ corresponds to 1.03 mm per 30 days of precipitation minus evaporation. Decomposition of $LQ_{\rm adv}$ into MMC, SE and TE components is shown in Figs. 9 and 10, with corresponding results by NO+.

The magnitude of time change, $\Delta\langle q\rangle/\Delta t$, is much smaller in SPC (Fig. 8) than in NPC (Fig. 7). In NPC, this term is positive in spring to summer and negative in autumn. The same tendency is found in SPC, though the signal is small.

In NPC, Q_{adv} is large in summer, reflecting the seasonal variation of moisture content. $-Q_{sfc}$ (precipitation minus evaporation) has a maximum in late summer. The annual total value of precipitation minus evaporation is 155 mm. This value agrees with the result of NO88 (122 mm), while it is much larger than the hydrological estimate, 62 mm, by BAUMGARTNER and REICHEL (1975).

The annual precipitation minus evaporation for SPC (148 mm) is similar to that for NPC according to the present analysis. It incidentally agrees with 153 mm due to BAUMGARTNER and REICHEL (1975). On the other hand, the discussion in the energy budget section leads to the consequence that the actual precipitation minus evaporation is likely to be smaller than 148 mm, because stronger MMC implies larger advective loss of water vapor from Antarctica.

The seasonal variations of Q_{adv} and $-Q_{sfc}$ are fairly flat with a minimum in December. The seasonal cycle of precipitation at various locations of Antarctica is shown by DOLGIN and PETROV (1977; as quoted by BROMWICH, 1988). In some areas precipitation is highest in winter and in others in autumn; none of the curves has a maximum in December. Thus, it seems probable that the seasonal variation of $-Q_{sfc}$ shown in Fig. 8 reflects reality to some extent, though the magnitude is likely to be biased.

6. Concluding Remarks

For NPC, fair agreement between the present results and independent analyses by NAKAMURA and OORT (1988) suggest that we know enough about the Arctic atmosphere to discuss the seasonal variation of heat and water budgets. The annual total balance is less confidently known.

For SPC, the situation is not satisfactory. In particular, the advective transport of energy (and probably of water vapor) due to the mean meridional circulation is still porly konown. The bias resulting from FGGE data happened to be opposite to that from OORT's (1983) statistics. The inconsistency of mass transport brings large uncertainty about MMC. Another problem of SPC is the sparseness of observing stations. The rawinsonde network in the 1963–73 period is shown in Fig. 2b of NO88. Though augmented by satellite observations etc., the situation in the Antarctic was not much better during FGGE. Regrettably, there were no stations in Western Antarctica (except Antarctic Peninsula) that routinely conducted radiosonde observations in 1979. At present, the most accurate budget analysis of Antarctic atmosphere we can perform would be that of a polygon connecting radiosonde stations surrounding the Eastern Antarctic subcontinent, as done by BROMWICH (1979), As he notes (see SCHWERDTFEGER, 1984, Section 5.2.1), great attention should be paid to the vertical resolution near the surface. Hopefully in the future, we will be able to quantitatively discuss energy and water cycle of the Antarctic, provided that we have

* a little more enhanced upper-air observation network

and

∗ a data assimilation system with more attention to mass conservation.

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