A Possible Change in Mass Balance of Greenland and Antarctic Ice Sheets in the Coming Century

ATSUMU OHMURA AND MARTIN WILD

Department of Geography, Swiss Federal Institute of Technology, Zurich, Switzerland

LENNART BENGTSSON

Max Planck Institute for Meteorology, Hamburg, Germany

ABSTRACT

A high-resolution GCM is found to simulate precipitation and surface energy balance of high latitudes with high accuracy. This opens new possibilities to investigate the future mass balance of polar glaciers and its effect on sea level. The surface mass balance of the Greenland and the Antarctic ice sheets is simulated using the ECHAM3 GCM with T106 horizontal resolution. With this model, two 5-year integrations for the present and doubled carbon dioxide conditions based on the boundary conditions provided by the ECHAM1/T21 transient experiment have been conducted. A comparison of the two experiments over Greenland and Antarctica shows to what extent the effect of climate change on the mass balance on the two largest glaciers of the world can differ. On Greenland one sees a slight decrease in accumulation and a substantial increase in melt, while on Antarctica a large increase in accumulation without melt is projected. Translating the mass balances into terms of sea-level equivalent, the Greenland discharge causes a sea level rise of 1.1 mm yr^{-1}, while the accumulation on Antarctica tends to lower it by 0.9 mm yr^{-1}. The change in the combined mass balance of the two continents is almost zero. The sea level change of the next century can be affected more effectively by the thermal expansion of seawater and the mass balance of smaller glaciers outside of Greenland and Antarctica.

1. Introduction

The glacier mass balance is considered to play a significant role in influencing global sea level, besides other potential mechanisms such as the thermal expansion of seawater and the earth's crustal movements. The ice sheets on Greenland and Antarctica are considered especially important because of their large surface areas and ice volumes. In the short term, glacier total mass balance is influenced more by the surface area than the volume. The Greenland and the Antarctic ice sheets occupy 1.75 and 13.92 ($\times 10^6$ km^2), respectively, corresponding to 10.9% and 85.7% of the total global glacier surface (Haeberli et al. 1989). Under the concept of an ice sheet, in the context of this work, small glaciers on Greenland and Antarctica are also included. In the long term, ice volume becomes important. Greenland (2.65×10^6 km^3) and Antarctica (30.11×10^6 km^3; Drewry 1983) make up 99.8% of

the total global glacier ice volume (Ohmura 1987b, 1994). These ice volumes are equivalent to sea level changes of 6.7 m and 67.9 m, respectively, without considering the effect of hydroisostasy. The combined contribution of all other glaciers to the sea level increase is only about 15 to 27 cm, depending on the assumption of the mean ice thickness of smaller glaciers. This consideration places both ice sheets at the front of importance in evaluating the causes of sea level change. Simulation of the mass balance change of the ice sheets under the near future climate has so far been hampered by the difficulty in estimating future precipitation on glaciers. In the past, the future mass balance of the ice sheets was calculated by either assuming certain scenarios or keeping precipitation constant (Oerlemans et al. 1991). Reactions of glaciers following climate changes were also investigated in the form of sensitivity tests by Kuhn (1980) and Ambach (1985). In recent years, however, it has become possible to simulate future precipitation with better confidence because of the transient experiments with GCMs. The problem of coarse grids, a necessary characteristic for a long-range transient experiment, can be overcome by driving a high-resolution GCM for a limited duration of time using the boundary conditions (SST and sea

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Corresponding author address: Dr. Atsumu Ohmura, Department of Geography, Swiss Federal Institute of Technology (ETH), Winterhurerstrasse 190, CH-8057 Zurich, Switzerland.
e-mail: ohmura@geo.umnw.ethz.ch

ice) provided by the transient experiment. This method is considered to be superior to a mere nesting of a mesoscale model because the high-resolution GCM captures smaller-scale structures more effectively on the global scale.

2. GCM experiments

The present climate was simulated with the ECHAM3/T106 model for $5^1/_2$ years using observed boundary conditions of the mid-1980s. This control run was used to test the capability of the high-resolution GCM against the observed climate and as a reference for the $2 \times CO_2$ scenario experiment (Arpe et al. 1994). It is not feasible with today's supercomputing resources to run a high-resolution T106 atmospheric general circulation model coupled to an ocean general

circulation model over several decades as required in transient climatic change experiments. This can be overcome by a "time window experiment." Thereby the T106 atmospheric model is run with prescribed boundary conditions of sea surface temperature and sea ice at the time of doubled CO_2 taken from a low-resolution, fully coupled atmosphere–ocean transient GCM experiment. Such an experiment has been performed at the Max Planck Institute, where a T21 version of the ECHAM model coupled to a dynamic ocean model was integrated for 100 years with a gradual increase of CO_2 according to IPCC scenario A (Cubasch et al. 1992). The projected sea surface temperature and sea ice were averaged over the period when the doubling of CO_2 is expected (2040–2050) to serve as boundary conditions for the T106 run. Forced with these boundary conditions and a doubled CO_2 concen-
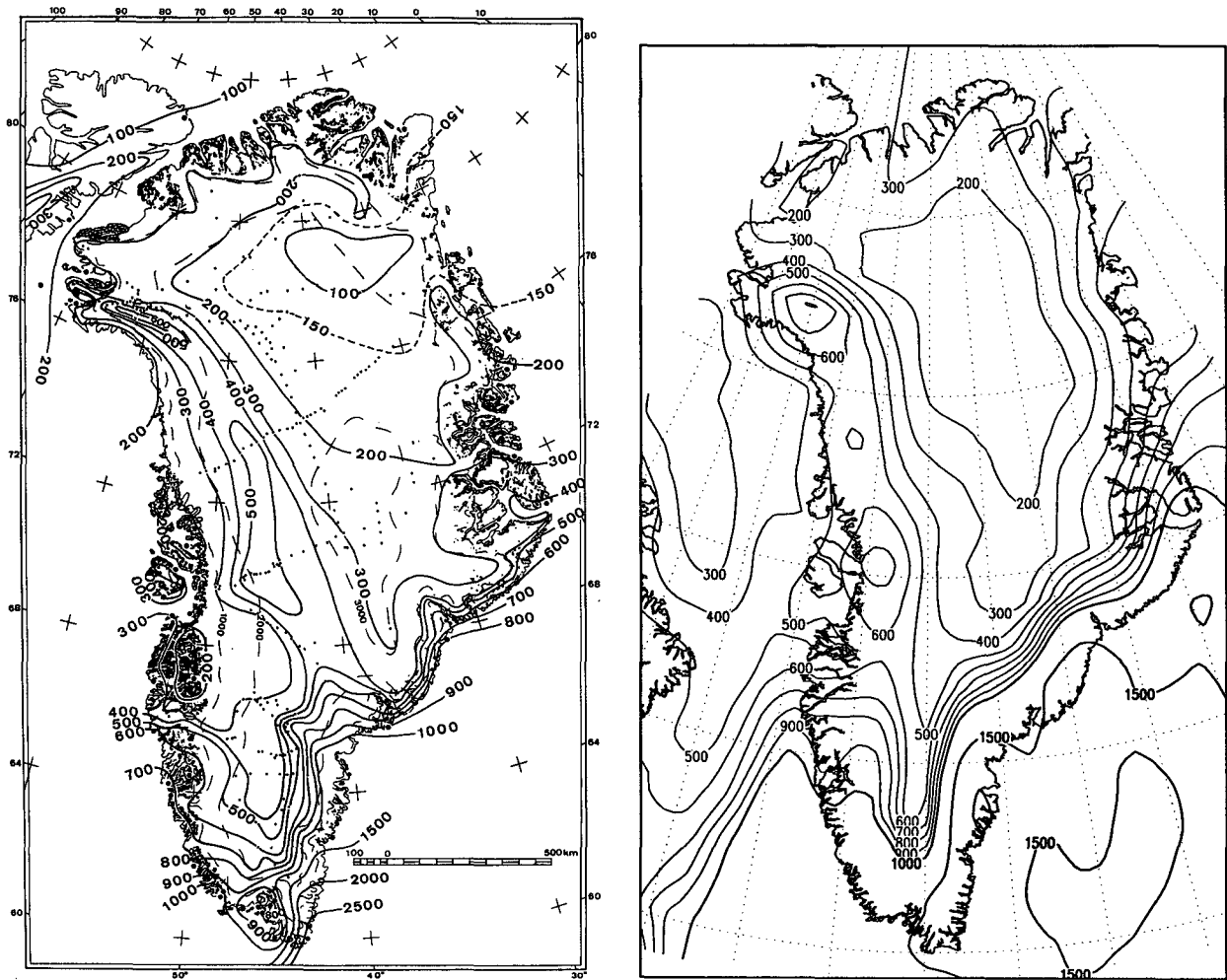

FIG. 1. Comparison of the computed (right) and observed (left) annual total precipitation in millimeters for Greenland. Source for the observed is Ohmura and Reeh (1991).
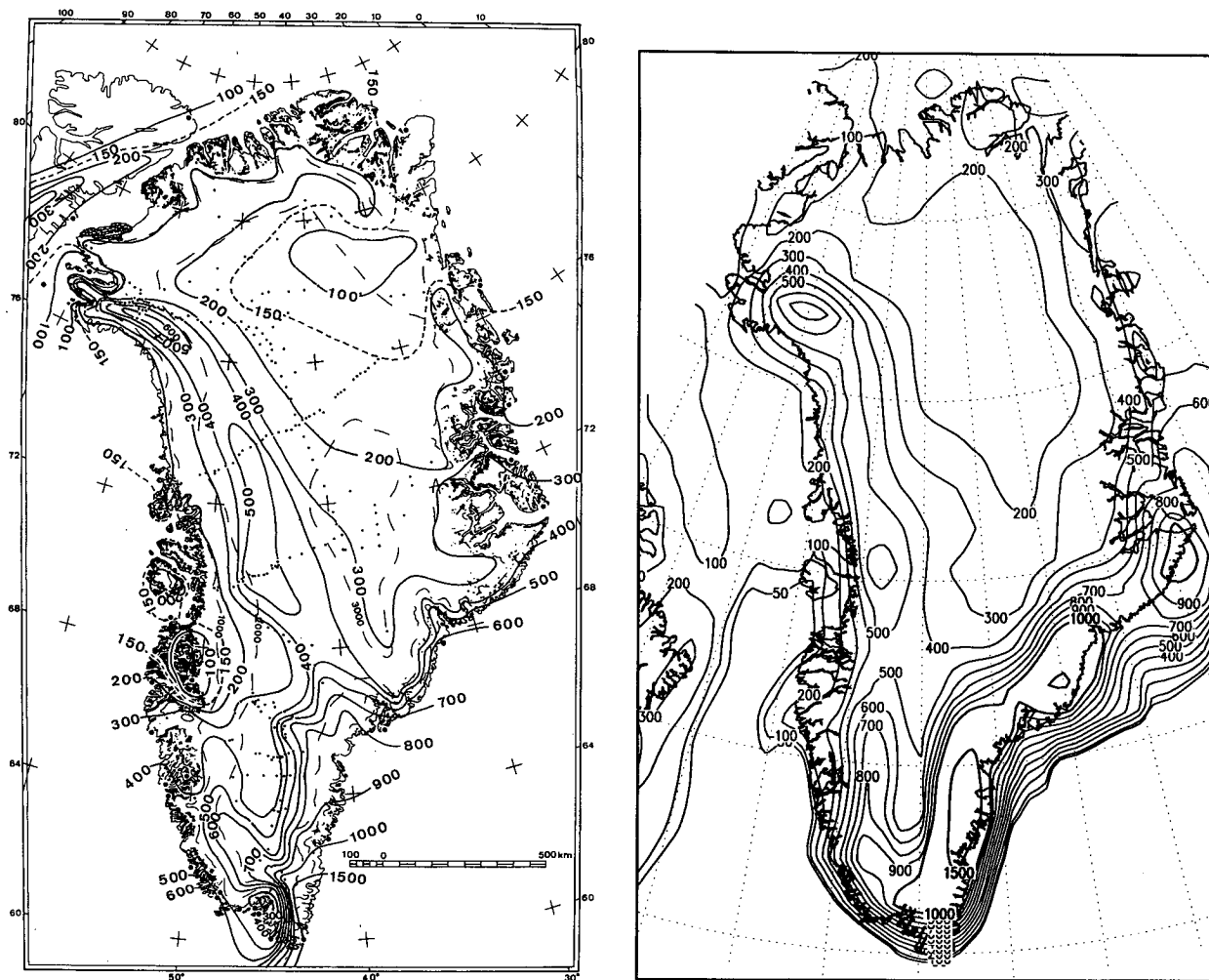
FIG. 2. Comparison of the computed (right) and observed (left) annual accumulation in millimeters.
Source for the observed is Ohmura and Reeh (1991).

tration, the T106 model was then integrated for 5 1/2 years.

In view of the high degree of accuracy of the control run in simulating the present-day precipitation distribution, it is judged appropriate to use this method to compute the future mass balances of Greenland and Antarctica and to assess their contributions for sea level change. At this stage the time domain considered is one century. This rather short time domain allows us to consider the mass balance problem purely as a surface exchange phenomenon without involving dynamic aspects such as changes in geometry and calving. The dynamic effects become important when the ice sheet is coupled with the climate model for durations longer than 1000 years (Abe-Ouchi 1993).

3. Present and future precipitation and accumulation

The capability of ECHAM3/T106 to simulate the present precipitation can be seen in Figs. 1, 2, and 3. The observed annual precipitation distributions are based on accumulation studies and long-term meteorological observations (Giovinetto et al. 1990; Ohmura and Reeh 1991). The model-computed precipitation maps reveal a high degree of success in simulating the major geographical patterns of precipitation and also the absolute values. To achieve an accurate simulation of local details and regional averages, the improvement in horizontal resolution and hence topography is essential. For all of Greenland the three experiments, T21, T42, and T106, produced annual mean precipitation of
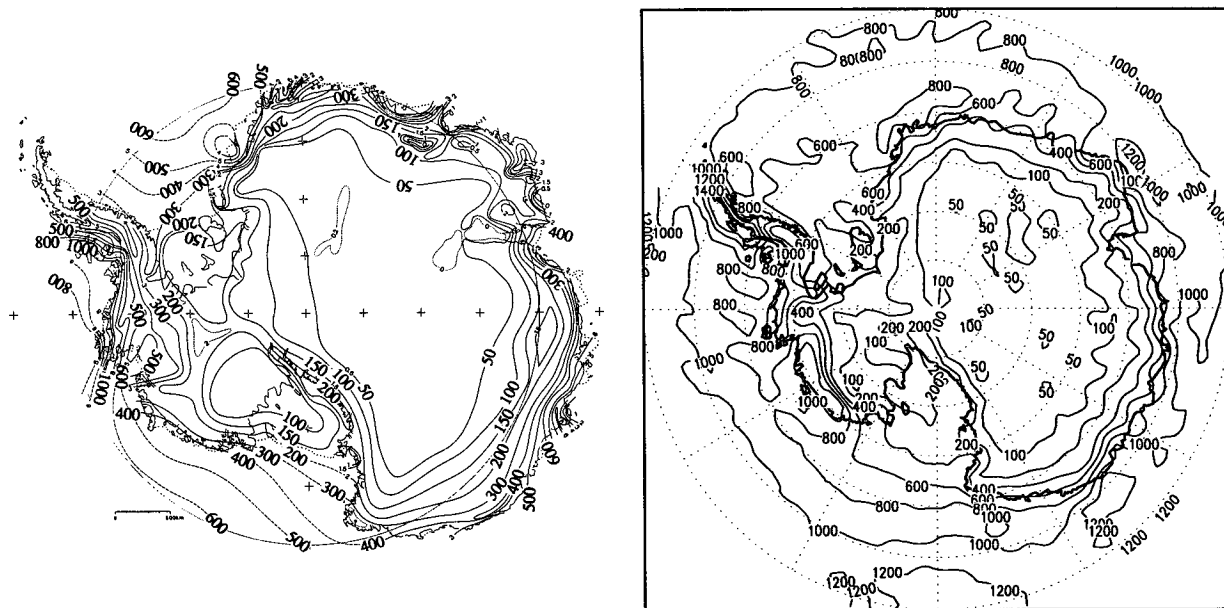
FIG. 3. Comparison of the computed (right) and observed (left) annual total precipitation
for Antarctica in millimeters. Source for the observed is Giovinetto et al. (1990).

785, 585, and 495 mm, respectively. As the resolution was increased, the topographic barrier of Greenland succeeded in preventing the northward penetration of the Atlantic air mass and an overestimation of precipitation was avoided. Examining individual years of the T106 experiment, the annual mean precipitation ranges from a minimum 425 mm to a maximum 550 mm with a standard deviation of 45 mm. Improvement in the regional simulation of precipitation by introducing higher horizontal resolution was reported by Genthon et al. (1994) with the Météo-France Arpège GCM, T21, T42, and T79 experiments.

For Greenland, the occurrence of the greatest precipitation on the southeast coast, the sharp latitudinal gradient on the southwest coast, the zone of high precipitation on the west slope culminating in a maximum north of Melville Bay and the driest area north of the Summit are well represented. The seasonal course of regional precipitation, such as the winter maximum on the southeast coast and the summer maximum on the west coast, is also realistically simulated. This capability is crucial for the simulation of the accumulation in the future climate.

On Antarctica the main features are well captured (Fig. 3); they are generally drier East Antarctica, wet-

TABLE 1. Mass balance for the present and for the time of doubled CO_2 for Greenland.
Units are in millimeters water equivalent per year.

	Observations	Model experiments		
		Control	$2 \times CO_2$	$2 \times CO_2$ − Control
1) Annual precipitation	340	494 ± 45	492 ± 45	−2
2) Annual accumulation or solid precipitation minus evaporation	317	426	405	−21
3) Annual ablation based on energy balance		228	425	197
4) Annual ablation based on summer temperature	200	146	353	208
5) Storage change and calving				
2 minus 3		198	−20	−218
2 minus 4	117	280	52	−229
Sources	Ohmura and Reeh (1991)		This study	

TABLE 2. Mass balance for the present and for the time of the doubled CO_2 for Antarctica. Units are in millimeters WE per year.

		Model experiments		
	Observation	Control	$2 \times CO_2$	$2 \times CO_2$ − Control
1) Annual precipitation	184 ± 37	224 ± 8	249 ± 9	25
2) Annual accumulation or solid precipitation minus evaporation	184 ± 37	197	220	23
3) Storage change and calving	Unknown	197	220	23
Source[a]	Giovinetto et al. (1992)		This study	

[a] There are other observed accumulation values, such as 143 mm (Giovinetto and Bull 1987), 151–156 mm (Bromwich 1990), 135 mm (Yamazaki 1994), and 147 mm (Peixoto and Oort 1992).

ter West Antarctica with a sharp gradient near the coasts, lower precipitation on Ross and Filchner Ice Shelves, and a distinctive contrast between the east and west coasts of the Antarctic Peninsula. On a much more regional scale, the ECHAM 3/T106 experiment captures such fine features as larger precipitation gradients
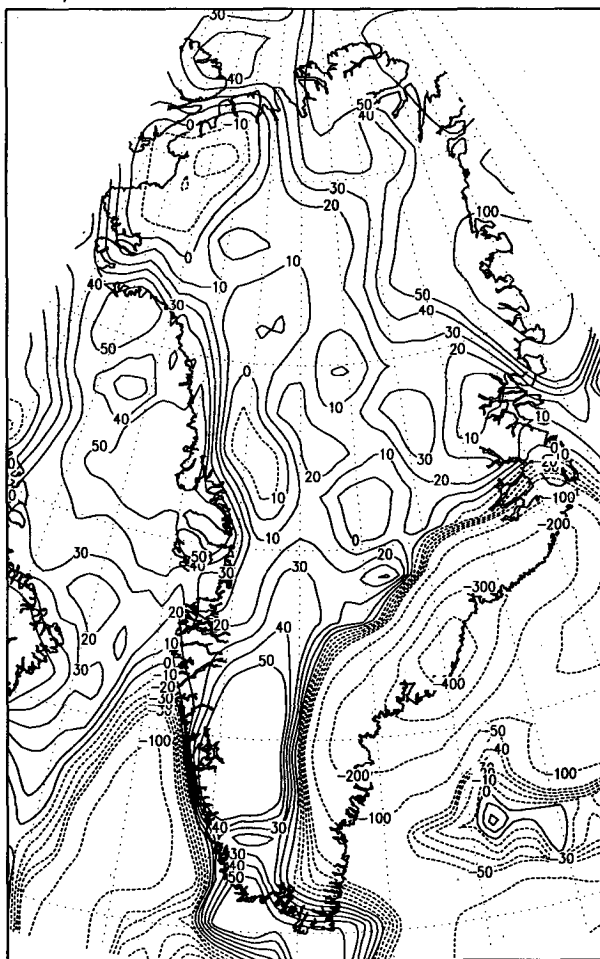

FIG. 4. Difference in annual total precipitation, $2 \times CO_2$ minus $1 \times CO_2$ for Greenland (unit in millimeters).
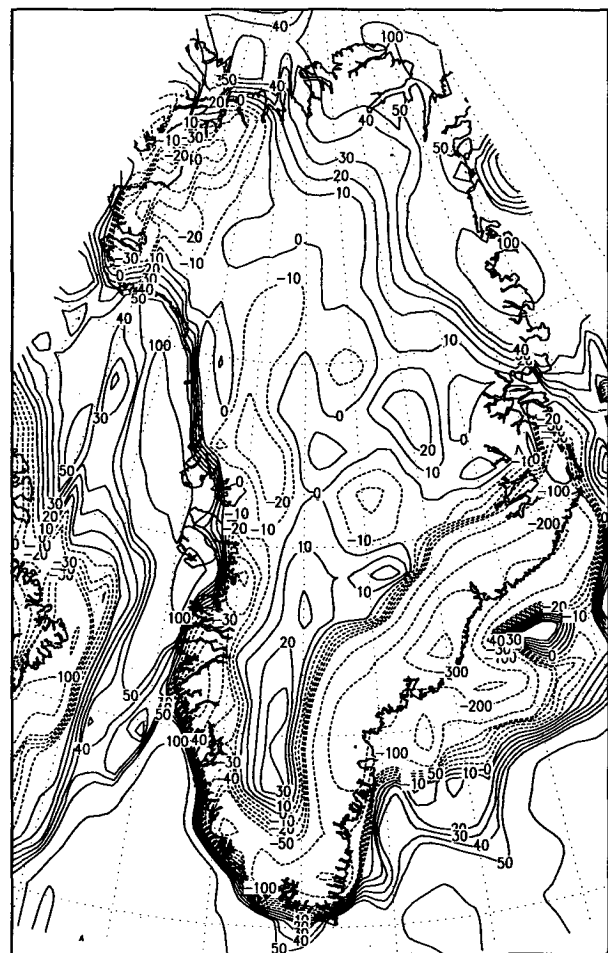

FIG. 5. Difference in annual accumulation, $2 \times CO_2$ minus $1 \times CO_2$ for Greenland (unit in millimeters).
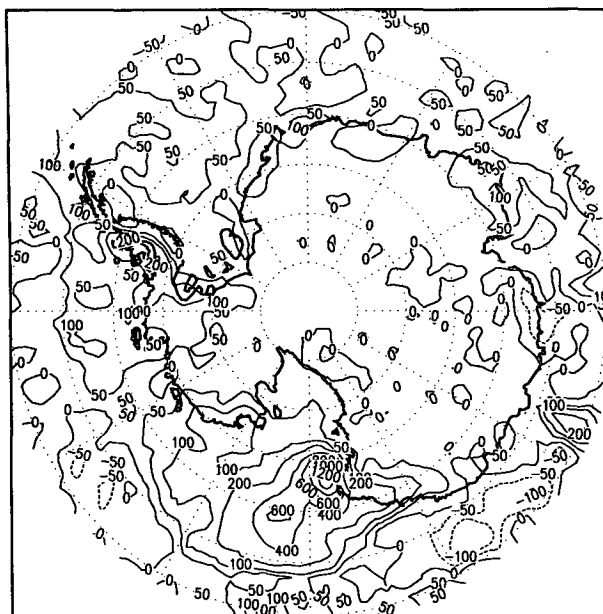
FIG. 6. Difference in annual total precipitation, $2 \times CO_2$ minus $1 \times CO_2$ for Antarctica (unit in millimeters).

from the coast to the interior as observed on Princess Martha Coast and Enderby Land. A smaller gradient between these two regions around Prince Harald Coast is also clearly represented. It is also remarkable to see that the zone of maximum precipitation in East Antarctica around Wilkes Land is successfully simulated.

To evaluate the model capability of precipitation quantitatively, the mean accumulation was computed for Greenland and Antarctica and compared against the observed means (Tables 1 and 2). The computed accumulation is defined as the difference of solid precipitation and evaporation, both of which are model-computed. This quantity is considered to be more directly comparable to the observed accumulation, as the evaporative loss is automatically taken into account in the core and pit observations. For Greenland and Antarctica, the model computations give on an average 10 and 5 cm liquid water equivalent more accumulation than the observations, respectively. Regarding this small difference, one cannot simply conclude an overestimation in the computation, as the observed distributions are more likely underestimated. The conventional precipitation measurements are prone to underestimation (Sevruk 1993). An overestimation for the computation is, however, caused in part through the mass loss by drifting snow off the coastal line, which is not included in the model computation. For Antarctica the observed accumulation by Giovinetto et al. (1992) in Table 2 takes drift loss into account. The small difference be-

tween their value of 184 ± 37 mm and 197 mm computed accumulation gives confidence in the simulation capability of the precipitation in the present experiment. A comparison of the T106 with the other coarser-grid experiments such as T21 and T42 based also on the same ECHAM 3 indicates that by increasing horizontal resolution the precipitation is probably the most improved element. Globally even the T106 model presents a serious underestimation of the summer precipitation for midlatitudes. The cause of this underestimation is known to be the difficulty to produce precipitation from convective clouds. The success of the precipitation simulation for polar regions is mainly because the precipitation on Greenland and Antarctica is not derived from convective clouds.

For the doubled CO_2 climate, annual total precipitation (Fig. 4) over Greenland increases by about 30 mm yr^{-1} in most regions, except for the coastal zone in the southeast and on the northwestern slope around Melville Bay. The significant decrease in the southeast Greenland where presently the largest accumulation is observed occurs throughout the year owing to weakening of the Icelandic low. A somewhat weak decrease on the west slope is observed only during warmer months, owing to the weakening of the eastward migrating cyclones from the Canadian Arctic. The regions with a large increase in precipitation are expected in the southwestern and northeastern region of the ice sheet. Averaged for the entire ice sheet the change is a decrease in annual precipitation of 2 mm yr^{-1}, mainly owing to the drastic decrease on the southeast coast. Solid precipitation (Fig. 5), however, decreases by 12 mm yr^{-1} owing to the temperature increase. This is an important difference in the change in precipitation for Greenland in comparison with that for Antarctica. That the precipitation on Greenland is influenced strongly by the change in atmospheric circulation during the last glacial–interglacial period was reported by Kapsner et al. (1995), based on the GISP2 ice core analyses. When a slight increase in evaporative loss is taken into account, the doubled CO_2 causes an accumulation decrease of 21 mm yr^{-1}.

For Antarctica all precipitation is accounted for as solid for both control and doubled CO_2 cases. In Antarctica an increase exceeding 100 mm yr^{-1} appears in Victoria Land, Ellsworth Land, Marie Byrd Land, and Enderby Land (Fig. 6). These are generally the regions where annual precipitation is greater in the present climate. Other regions with large precipitation under the present climate such as Princess Martha Coast and Adélie Coast, however, receive a modest increase of about 50 mm yr^{-1}. The increase in the interior region of East Antarctica remains small with 5 mm yr^{-1}. Ross Ice Shelf receives a moderate increase of 40 mm yr^{-1}, while the increase on Filchner Ice Shelf remains small at 10 mm yr^{-1}. Generally the increase in West Antarctica is greater, receiving
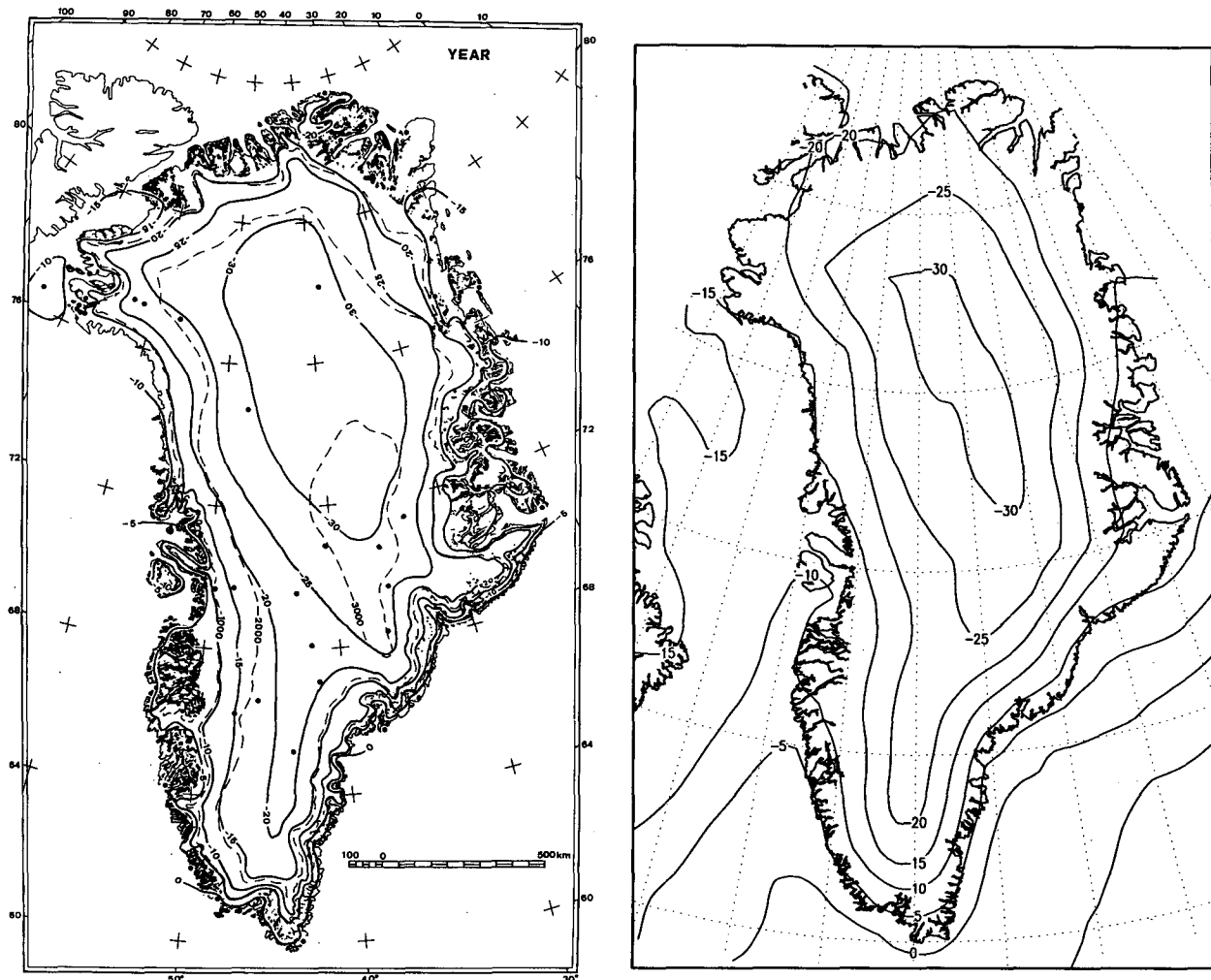
FIG. 7. Comparison of the computed (right) and observed (left) annual mean air temperature for Greenland.
Source for the observed is Ohmura (1987a).

45 mm yr^{-1}, than in East Antarctica where the regional average increase is only 20 mm yr^{-1}. Averaged for all of Antarctica, the increase is substantial at 25 mm yr^{-1}. There is a slight increase in evaporation under the doubled CO_2, which results in an increase in the annual accumulation of 23 mm yr^{-1}.

4. Present and future air temperature

As Figs. 7 and 8 show, the simulation capability of the present experiment for air temperature is extremely good. In detail, it can be said that for Greenland there is a small tendency for overestimation over the interior and underestimation over marginal zones throughout the year. The degree of these over- and underestimations is about 1°C. The error is smallest for altitudes of about 2000 m MSL. For Antarctica, small overesti-

mations are seen for the Antarctic Peninsula and Ross and Filchiner Ice Shelves. Generally the agreement with observation is slightly better for East Antarctica. Simulation of the annual mean temperature at the top of Dome A is within 1°C of observations.

After the doubling of CO_2, both for Greenland and Antarctica, the annual mean temperature increases by 2°C near the margin and by 4°C near the top of the ice sheets. An interesting aspect of the seasonal features is the altitude-dependent variations in temperature. It turns out that the often mentioned larger temperature increase is a characteristic of winter for lower elevations. The temperature increase over the interior region of both ice sheets seems to be similar in all seasons. The most important feature of the temperature increase over the ice sheets is the movement of the −2°C isothermal line for the three summer
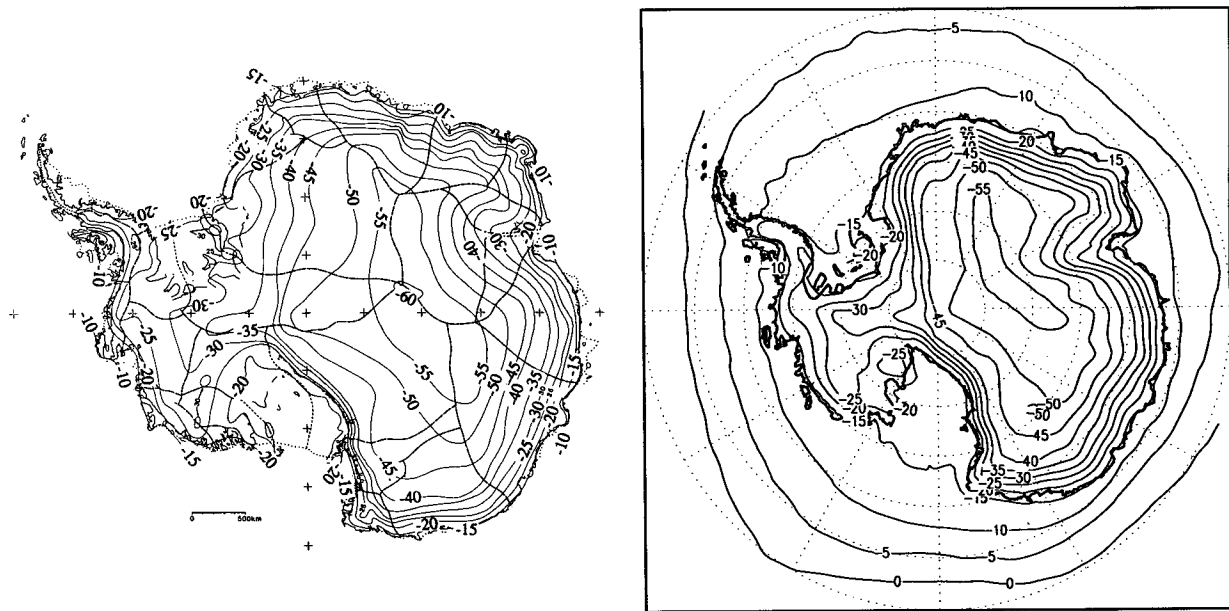
FIG. 8. Comparison of the computed (right) and observed (left) annual mean air temperature for Antarctica.
Source for the observed is Giovinetto et al. (1990).

months. The summer temperature of $-2°C$ is the minimum temperature where mass loss due to ablation can be expected as is presented in Fig. 9. On the Greenland ice sheet the $-2°C$ isothermal line for JJA appears presently at 1500 and 750 m MSL in southern and northern Greenland, respectively. The vertical shift of the line is 500 m in northern Greenland, while it is only 250 m in the south (Fig. 10). Because the surface gradient of the ice sheet is smaller in mid- and North Greenland where the surface area is larger, this regional trend contributes to a substantial increase in the melt. On the Antarctic ice sheet, the $-2°C$ isothermal line still remains outside of the ice sheet margin, even after the CO_2 is doubled. This temperature distribution indicates that the Antarctic ice sheet will not experience significant melt before the mid-twenty-first century.

5. Computation of the ablation

The computation of ablation on the Greenland ice sheet was done using two methods: The first is the melt computation based on the surface energy balance. Since ECHAM 3 does not compute the melting of snow and ice on glaciers, the sum of net radiation, sensible, and latent heat fluxes is first computed. This is the heat quantity that can be equated to the sum of the subsurface heat conduction and the latent heat of fusion. A comparison of the computed fluxes and those observed is presented in Fig. 11. The comparison was made for ETH Camp using 1991 summer observations. Details of the observational procedures are presented in Ohmura et al. (1992). The simulation capability of the present numerical experiment can be judged as sufficiently accurate for computation of the ice melt. The annual melt is assumed to be equal to the sum of the three components mentioned above, as the annual total subsurface heat flux can safely be assumed as zero. It must, however, be borne in mind that not all meltwater will be lost, as in cold glaciers a part of the meltwater could be retained on or in the glacier.

The second method is intended to compute the ablation and not merely melting. This computation is based on the observed relationship between the annual loss by the mass balance observations and the collocated mean air temperature for the summer three months of June, July, and August as is presented in Fig. 9. Therefore, in this method the surface refreeze is taken into account. A problem still remains to be addressed as to how much refreezing could occur in deeper layers of the ice sheet. Nevertheless, based on this relationship, the present ablation for the entire Greenland was computed by using the monthly temperature distribution maps by Ohmura (1987a). The present climatological ablation estimated in this method is 200 mm yr^{-1}. A similar estimation by the observed energy balance method is not possible, as the present coverage of Greenland with such observations is very sparse. The GCM-computed ablation in the con-
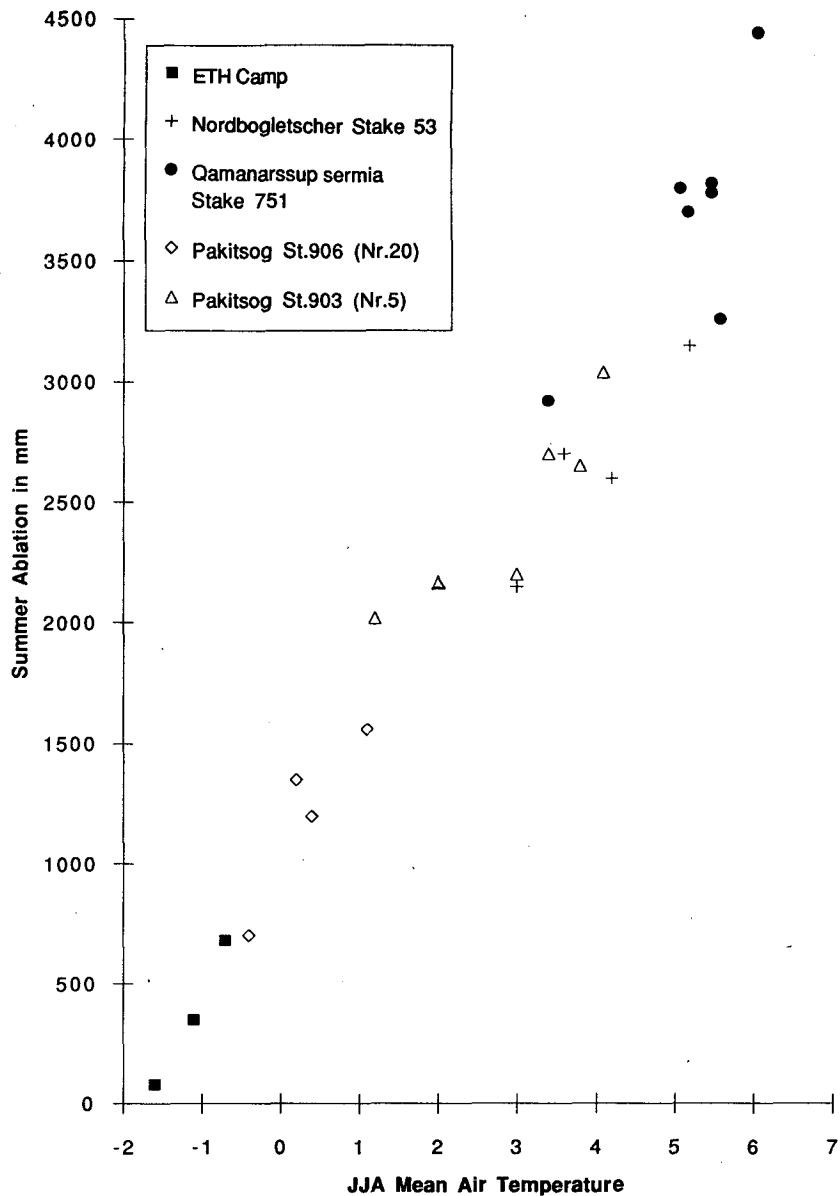
FIG. 9. Relationship between the annual total mass loss due to ablation and mean air temperature for June, July, and August for Greenland. Note that $-2°C$ is the minimum required temperature for the mass loss.

trol experiment gives 228 mm and 146 mm for the energy balance and the temperature/ablation methods, respectively. The energy-balance simulation of the ice melt is about 15% greater than the observed ablation. This difference may be decreased if the refreeze process is taken into account in the future. The underestimation of ablation by the temperature/ablation relationship is due to the underestimation of air temperature at lower altitudes, a general trend in the ECHAM3 tem-

perature simulation. The increase in ablation due to the doubling of CO_2 was estimated using the model-computed surface heat fluxes and the air temperature distributions for the present and the year 2050.

6. Present and future mass balance

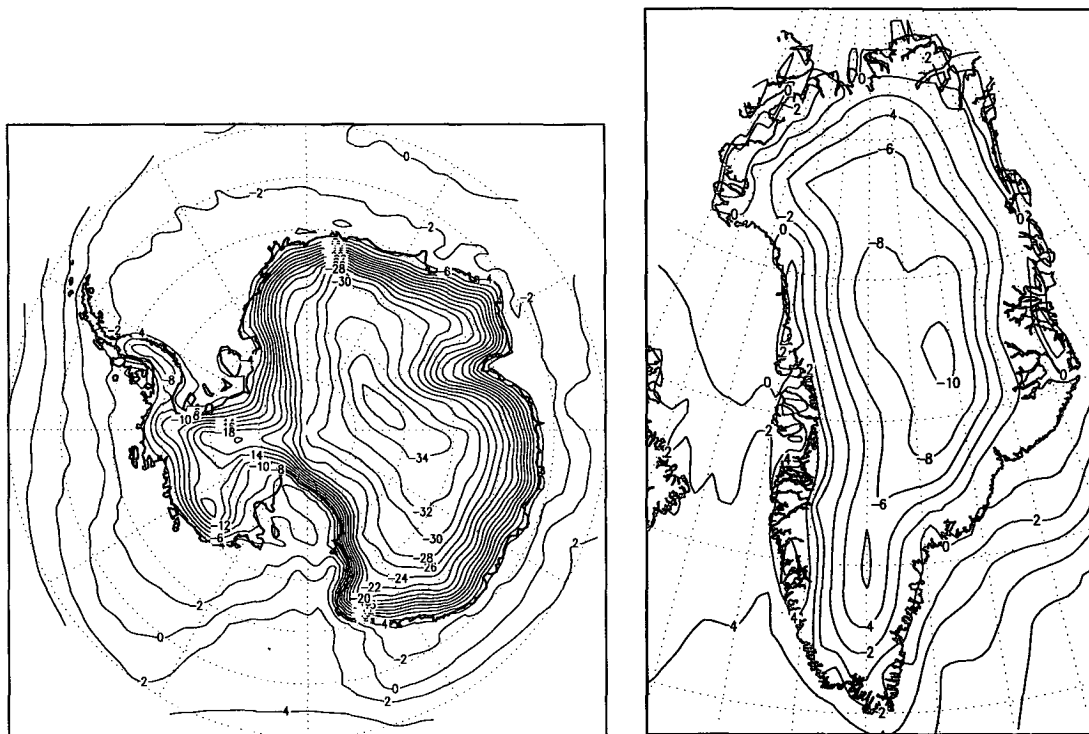For Greenland the increase in mass loss due to melting was calculated for the region in lower alti-

FIG. 10. Mean summer air temperature for Antarctica (Dec, Jan, and Feb) and Greenland (Jun, Jul, and Aug) expected under the doubled CO_2 condition.

tudes than the JJA mean isothermal line of $-2°C$ for the year 2050 stage. Components of the mass balance for Greenland are presented in Table 1 with respect to the present observation and this numerical experiment for the control and the doubled CO_2 cases. The energy balance method gives an annual increase in ice melt of 197 mm yr^{-1}, while the temperature-based approximation yields 208 mm yr^{-1}. It is remarkable that the two very different methods give an almost identical increase in the melt. The change in the mass balance on Greenland is characterized by a small decrease in mean annual specific accumulation (21 mm yr^{-1}) and by a substantial increase in the mean specific ablation (197–208 mm yr^{-1}). This calculation gives an annual total increase in the ablation of 380 to 400 km^3. The new mass balance for the Antarctic ice sheet is solely based on the increase in solid precipitation that projects an annual increase in accumulation of 325 km^3. It is important to note that the reaction of the two existing ice sheets toward the climate warming is extremely different. As Greenland discharges water to the oceans, Antarctica takes it up. The difference of the mass balance for Greenland and Antarctica is between 55 and 75 km^3, which becomes an annual increase of ocean water, corresponding to a sea level rise of about 0.18

mm yr^{-1}. The most important result of the present investigation is the prospect that the net contribution of glaciers in Greenland and Antarctica to sea level change in the mid-twenty-first century is practically zero.

7. Conclusions

The mass balance of the Greenland and Antarctic ice sheets for the period of the IPCC Scenario-A doubled CO_2 was simulated in the ECHAM3/T106, which was driven by the SST and sea ice distribution generated by the coupled atmosphere–ocean ECHAM1/T21 100-year transient experiment. It was found that Greenland showed a mean specific balance of -218 to -229 mm liquid water equivalent, while Antarctica gave $+23$ mm. Although the reactions of the two major ice sheets are very different, the combined effects tend to cancel each other, resulting in an annual sea level rise of about 0.18 mm yr^{-1}. For some time in the future the mass balances of the two largest glaciers may compensate each other. This result demonstrates that the role of thermal expansion of the oceans and the mass balance of glaciers outside Greenland and Antarctica may play a significant role in controlling future sea level elevations. A possible
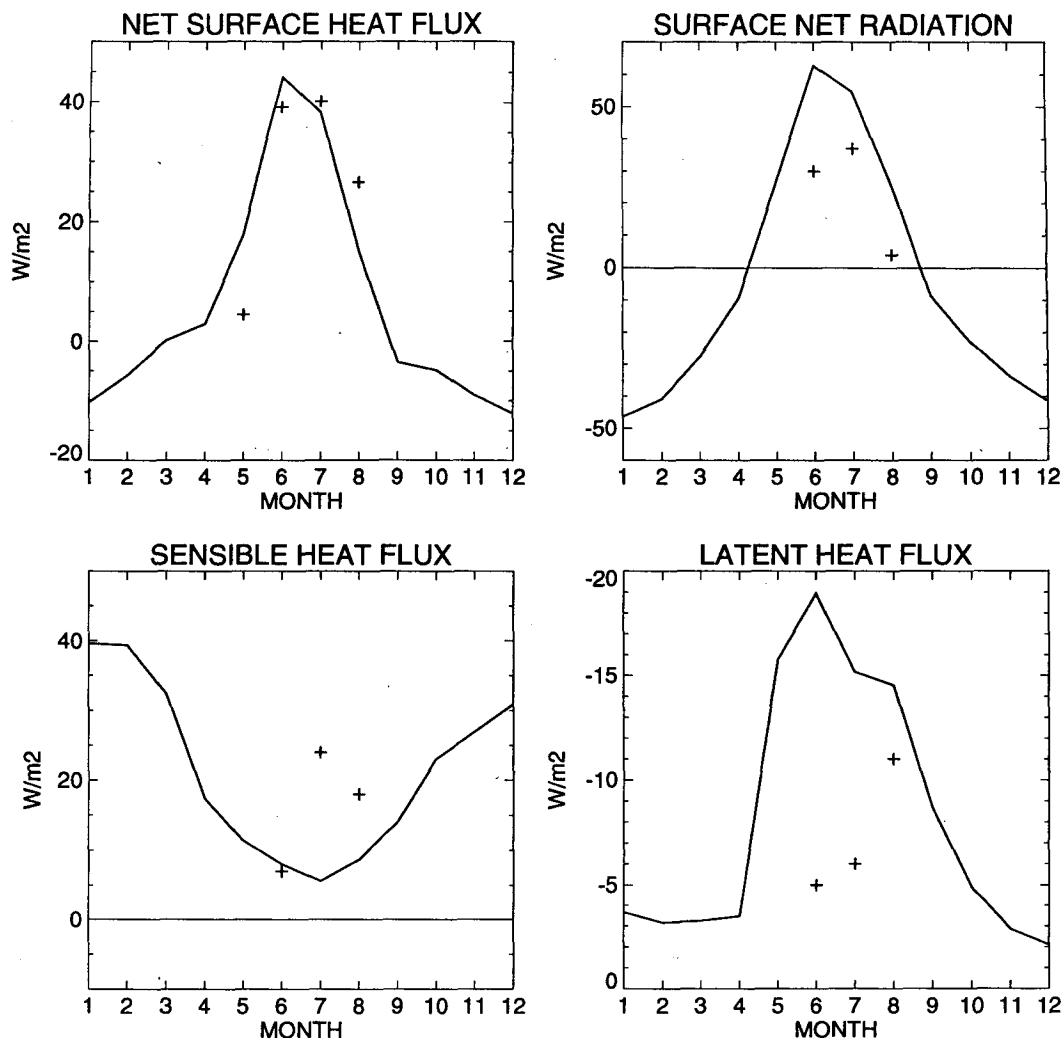
FIG. 11. Comparison of the computed (solid line) and observed (cross) monthly mean heat fluxes for ETH Camp. The details on the observations and the original data are presented in Ohmura et al. (1994). The observed flux (cross) in the net surface flux is the monthly total ablation, expressed in watts per square meter.

significance of small glaciers for the global sea level change was advocated by Meier (1984).

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